

DSMC SIMULATIONS FOR CUPID'S ARROW



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Advanced Modeling & Simulation Seminar

NASA Ames Research Center

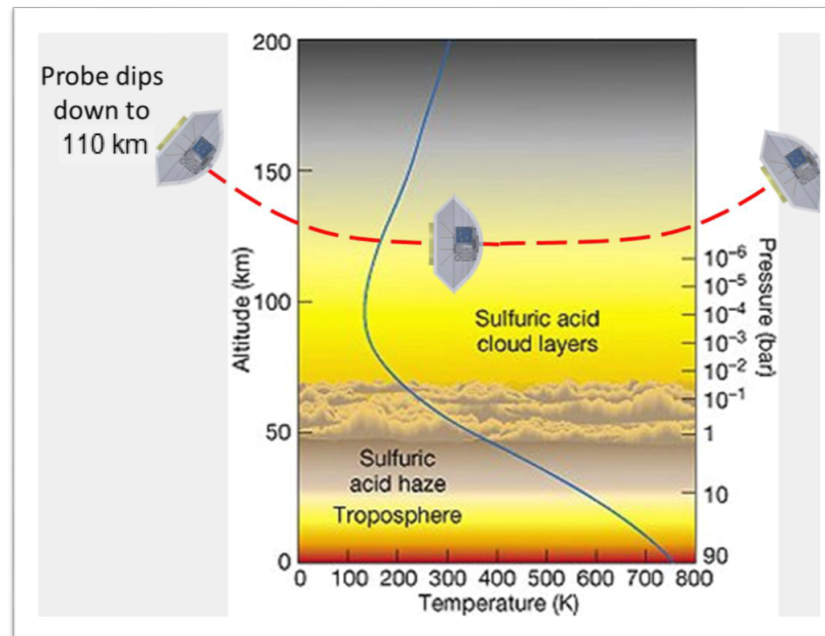
17th September 2020



Background

Previous work

- JPL has proposed mission concepts to NASA where a skimming probe traveling at ~ 11 km/s below Venus' homopause would collect atmospheric samples and then measure their content in noble gases and their isotopes with a miniaturized mass spectrometer. The mission concept study was funded through Planetary Science Deep Space SmallSat Studies - PSDS3 –program. A mission concept was part of the VOX Category 1 New Frontiers proposal.
- Are gas samples acquired while traveling at ~ 11 km/s representative of the free stream composition (for noble gases)? Can any changes be modeled?



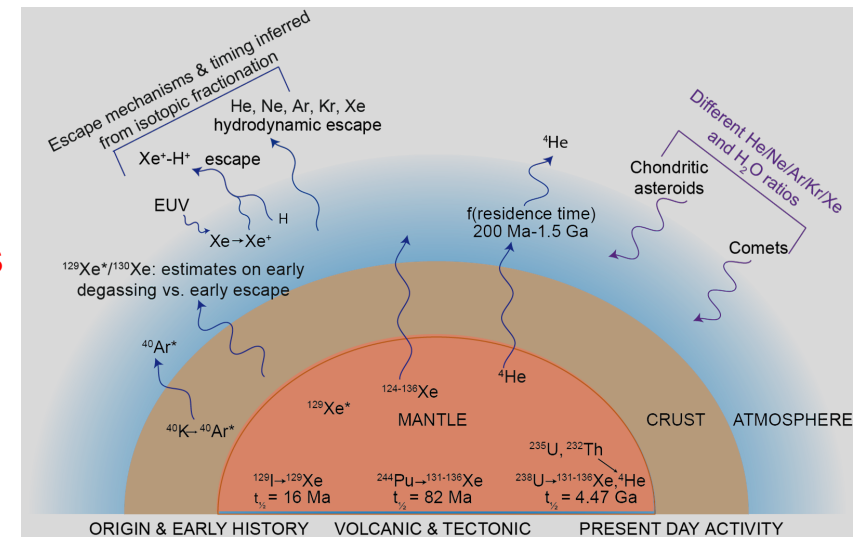
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URL: https://pages.uoregon.edu/jimbrau/BrauImNew/C_hap09/7th/AT_7e_Figure_09_17.jpg
Edited

Cupid's Arrow Science

Why is Venus so different than Earth?

- CA partly addresses US Planetary Decadal Survey Theme 1, specifically priority question 3: What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?

- Noble Gases are tracers of planetary evolution
 - the supply of volatiles from the solar nebula
 - the supply of volatiles by asteroids and comets
 - the escape rate of planetary atmospheres
 - the degassing of the interior (volcanism)
 - the timing of these events



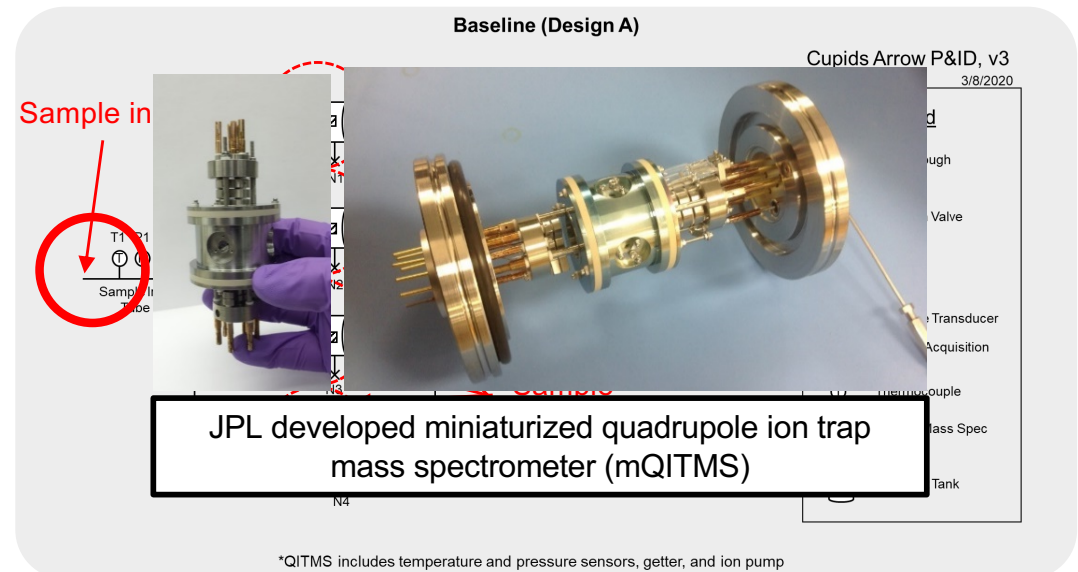
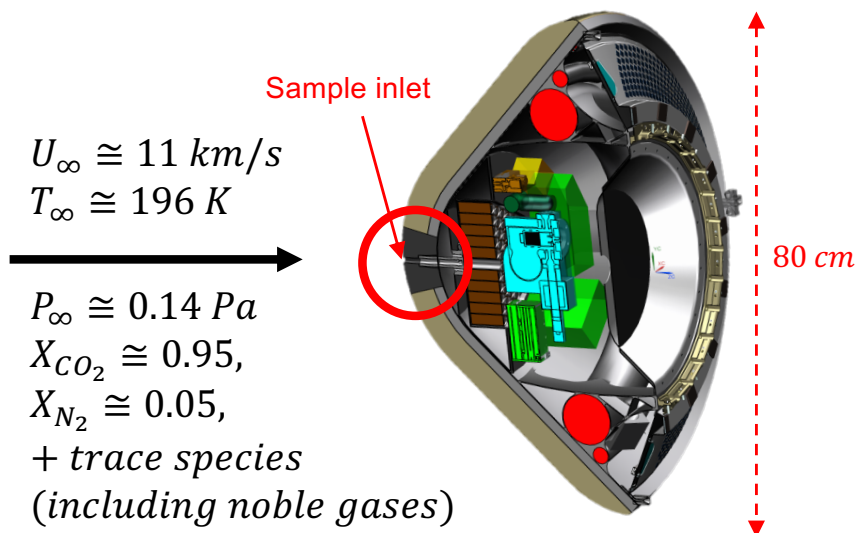
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 VOX New Frontiers' Proposal

- There are ~20 noble gases and their isotopes that can be measured (He, Ne, Ar, Kr, Xe).

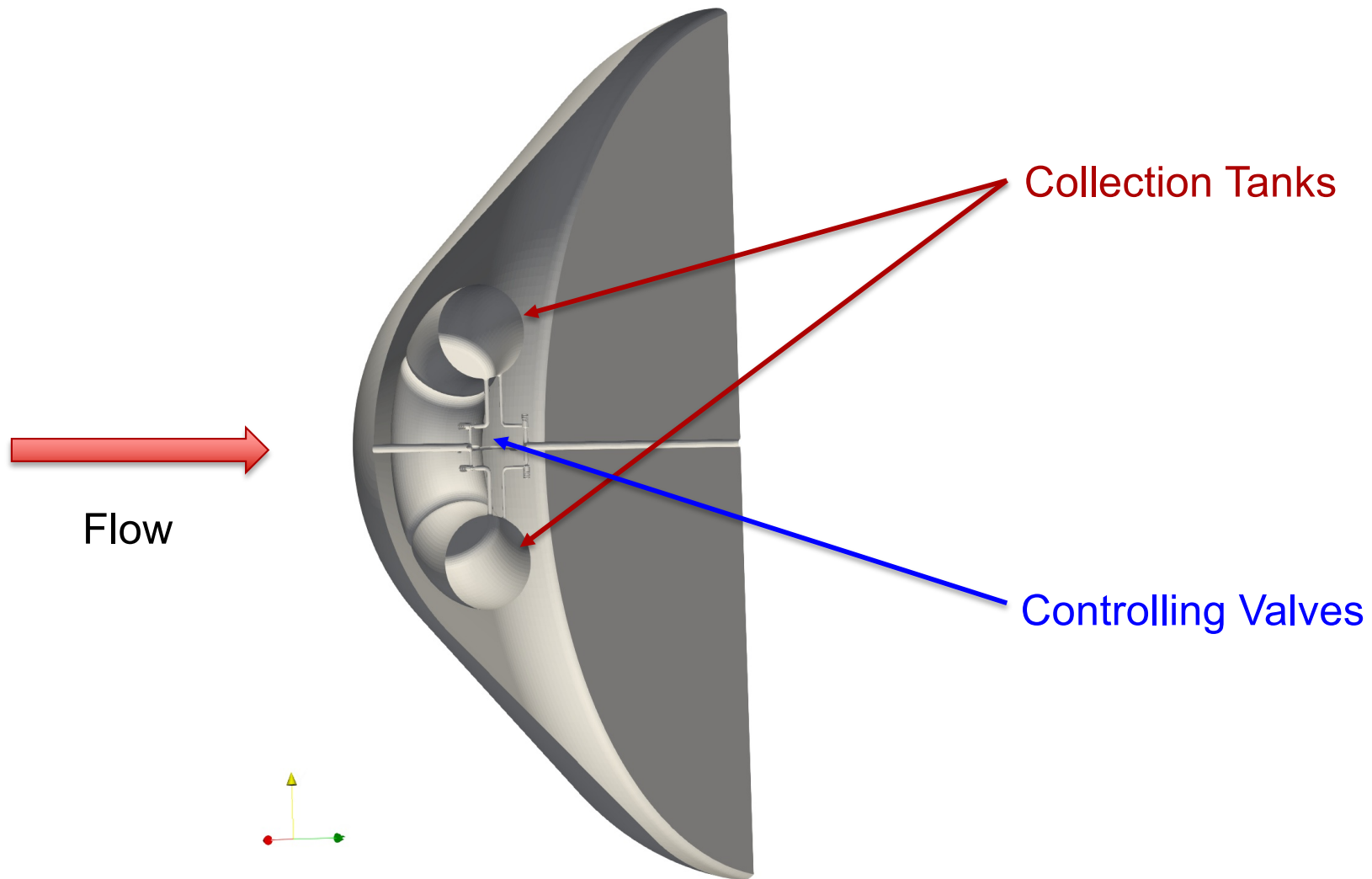
Cupid's Arrow Sampling

Sample Acquisition and Transfer System

- **Cupid's Arrow Mission Concept:** Venus atmospheric skimmer that samples the Venus atmosphere at ~ 110 km altitude, while traveling at ~ 11 km/s. It will measure noble gas concentrations with a JPL developed miniaturized quadrupole ion trap mass spectrometer (mQITMS).
- **Objective:** Measure noble gas concentrations and isotopic ratios to answer key scientific questions
- **Challenges:**
 - Venus atmospheric pressure is extremely low at 110 km (~ 0.1 Pa; ~1 mtorr) → very challenging to perform relevant experiments on the earth
 - Cleanliness requirements → many noble gases of interest are expected to have concentrations of ppb in the Venus atmosphere

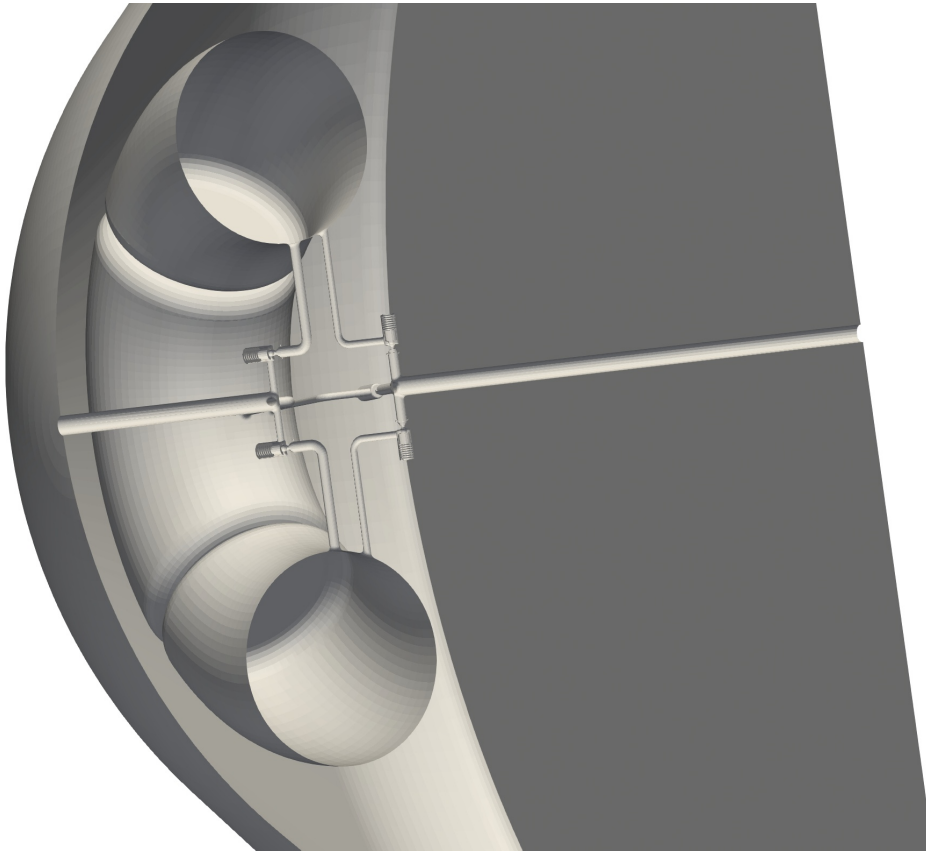


Cupid's Arrow Geometry

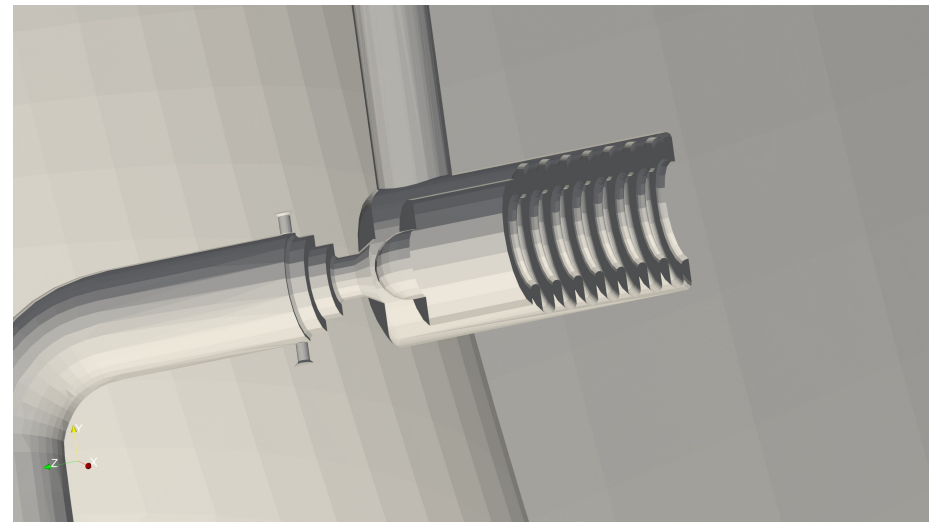
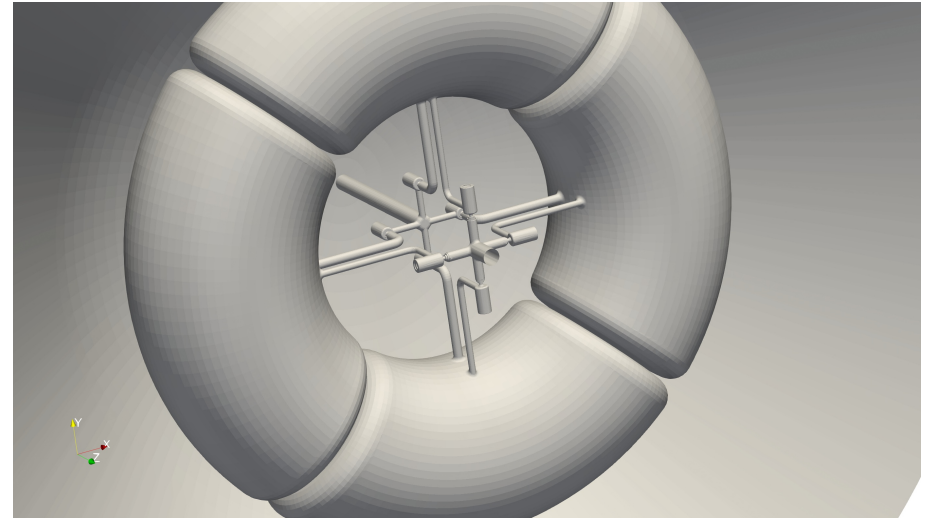


Geometry Details

Intent is to model a “flight-like” geometry



**Multiple length scales.
Local mean free paths range by a factor
of 1000.**

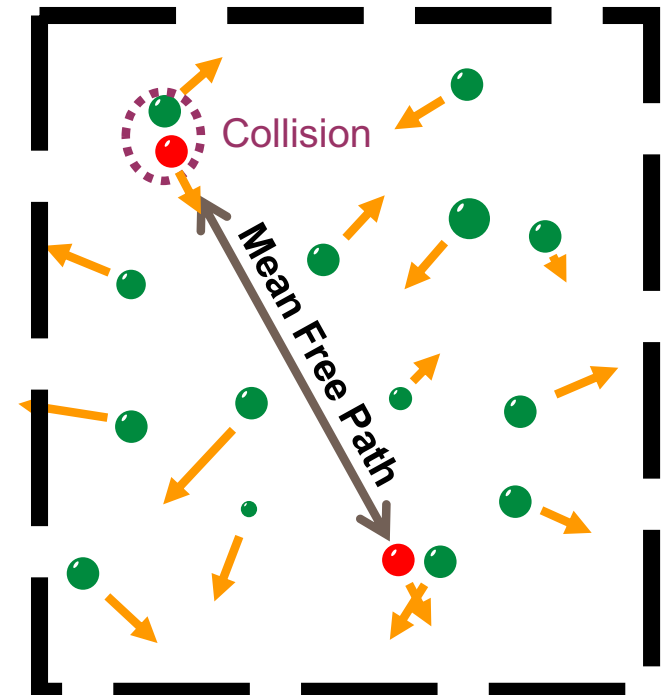
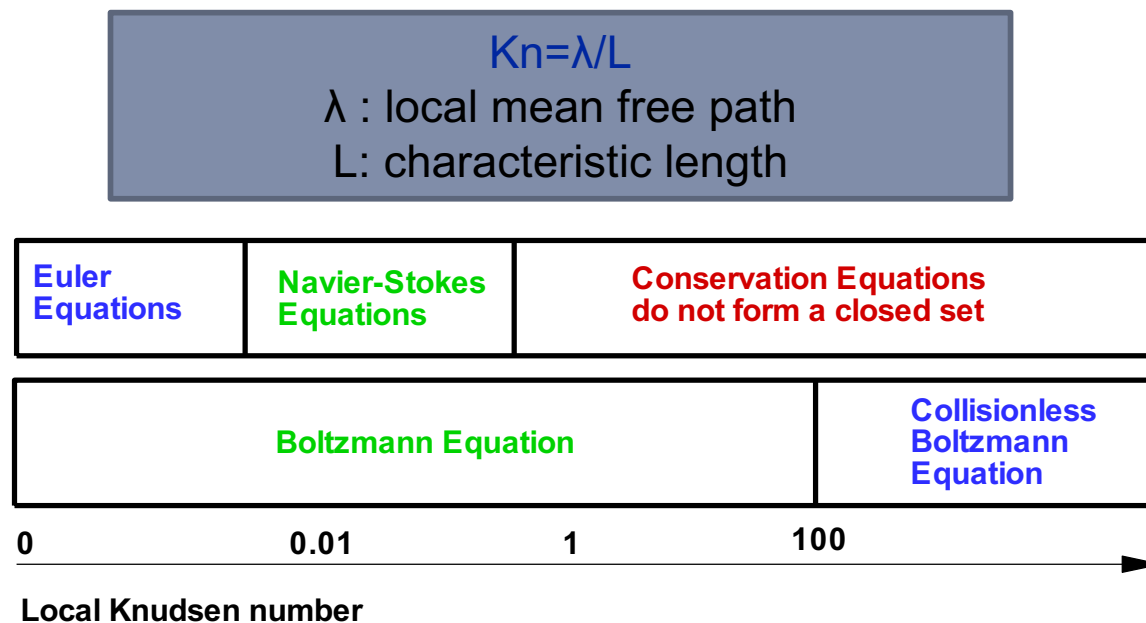


The Need for Molecular Gas Dynamics

Background

The **hydrodynamic description assumes** that changes in the fluid occur **slowly** so that the system can be considered in a state of local thermodynamic equilibrium.

If not, the fluid behavior **deviates from the predictions of hydrodynamics**, as molecular relaxation affects transport: diffusivity, viscosity, thermal conductivity.



Boltzmann Equation and the Direct Simulation Monte Carlo Method (DSMC)

Overview

Credit:
Wikipedia.
Public
Domain



Ludwig Boltzmann

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial \mathbf{v}} = \int_{-\infty}^{\infty} \int_0^{4\pi} (f^* f_1^* - f f_1) |\mathbf{v} - \mathbf{v}_1| \sigma d\Omega d\mathbf{v}_1$$

molecular motion and
force-induced acceleration

pairwise molecular collisions
(molecular chaos)



James Clerk Maxwell

Credit:
Wikipedia.
Public
Domain

$f(\mathbf{r}, \mathbf{c}, t) d^3 r d^3 c \rightarrow$ Expected number of molecules at time t in at $\mathbf{r} + d^3 r, \mathbf{c} + d^3 c$

$$n(\mathbf{r}, t) = \int f(\mathbf{r}, \mathbf{c}, t) d^3 c$$

The velocity distribution function can be replaced by a particle-based distribution function like the Klimontovich distribution function:

$$f(\mathbf{x}, \mathbf{v}, t) = \sum_{i=0}^N \delta^3(\mathbf{x} - \mathbf{x}_i(t)) \delta^3(\mathbf{v} - \mathbf{v}_i(t))$$

Substituting into the Boltzmann equation we have $2N$ differential equations:

$$d\mathbf{x}_i / dt = \mathbf{v}_i \quad d(m_i \mathbf{v}_i) / dt = \mathbf{F}(\mathbf{x}_i) + \mathbf{C}(\mathbf{v}_i)$$

molecules move

molecules collide

Boltzmann Equation and the Direct Simulation Monte Carlo Method (DSMC)

Overview

Credit:
Wikipedia.
Public
Domain



Ludwig Boltzmann

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial \mathbf{v}} = \int_{-\infty}^{\infty} \int_0^{4\pi} (f^* f_1^* - f f_1) |\mathbf{v} - \mathbf{v}_1| \sigma d\Omega d\mathbf{v}_1$$

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James Clerk Maxwell

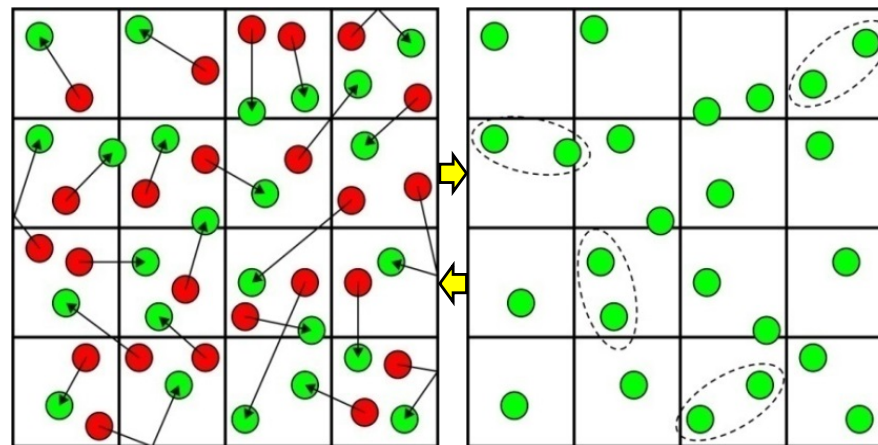
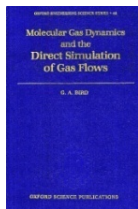
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$$n(\mathbf{r}, t) = \int f(\mathbf{r}, \mathbf{c}, t) d^3 c$$



Graeme Bird
(1963, 1994)



molecules move

molecules collide

DSMC has been shown to reproduce correctly the non-equilibrium behavior of a gas

Challenges

Validation

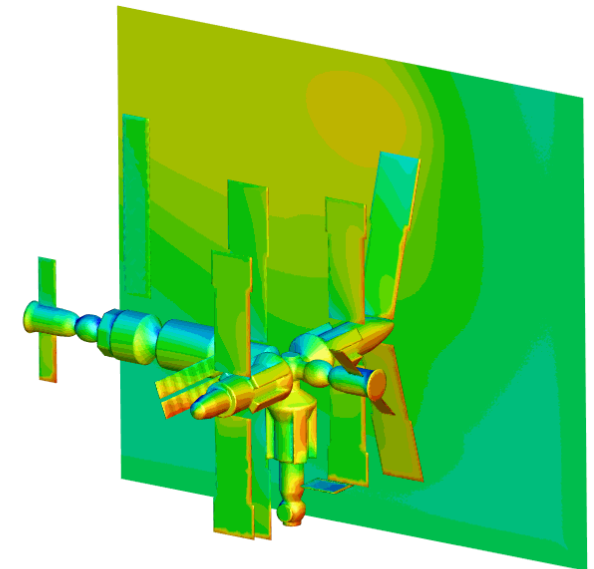
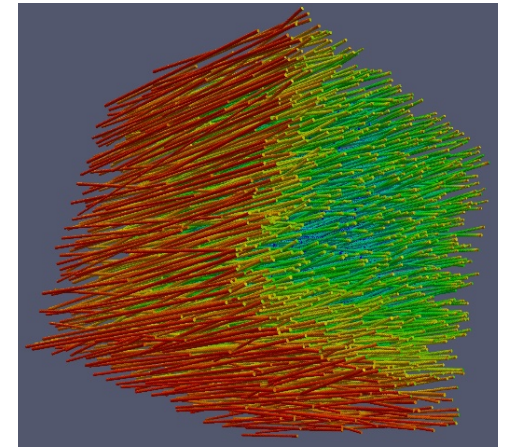
- DSMC provides the “validation” data
 - There is no theoretical or experimental confirmation for the whole system.
- Resort to “highest TRL” DSMC method (DSMC94).
 - Simple, tested, well understood models with known convergence behavior/error.
 - Molecular Model: VSS, Energy Exchange: Borgnakke-Larsen, Chemistry: TCE
- The geometry is complicated and spans multiple length scales.
 - Local mean free paths range by a factor of 1000.
 - Computationally the problem is extremely load imbalanced.
 - Small area where most of the molecules are cells are concentrated
- Kn maximum (freestream) 0.1, minimum (in the tube) 0.001, Kn (in the valve) 0.03

SPARTA: an Exascale DSMC Code

SPARTA = Stochastic PArallel Rarefied-gas Time-accurate Analyzer

General features

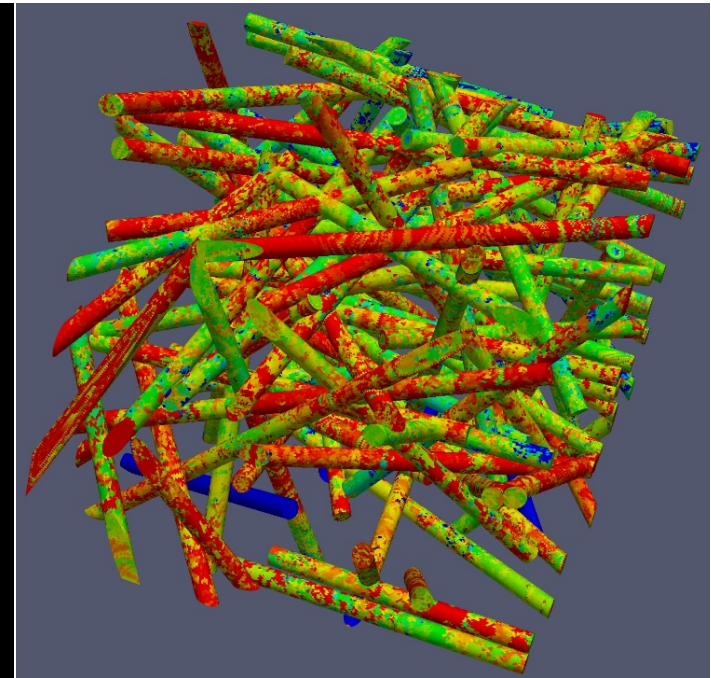
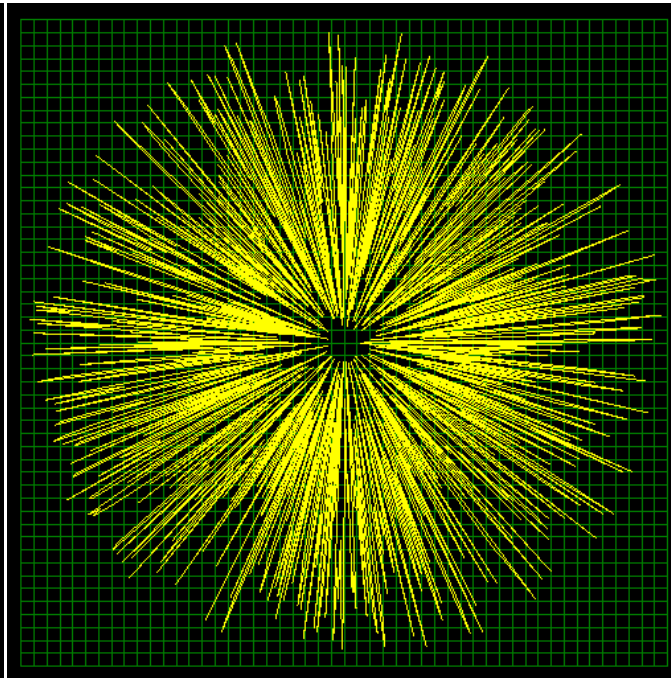
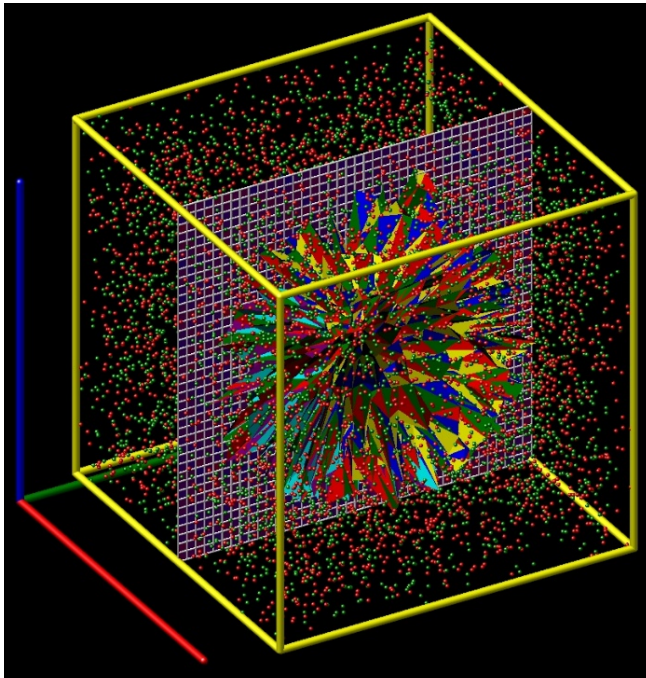
- 2D, 2D axisymmetric or 3D, serial or parallel
- Cartesian, hierarchical grid
 - Oct-tree (up to **16 levels in 64-bit cell ID**)
- Triangulated surfaces cut/split the grid cells
 - In-situ visualization, adaptive gridding, load balancing
- Aiming for next generation MPI
 - **Exascale capable**
 - Write application kernels only once, and
 - Run them efficiently on a wide variety of platforms:
 - GPU, Xeon Phi, etc.
- Open-source code available at <http://sparta.sandia.gov>
 - Product of collaboration between National Labs, NASA, academia and industry.
 - 3000+ downloads, 100+ users worldwide.



SPARTA

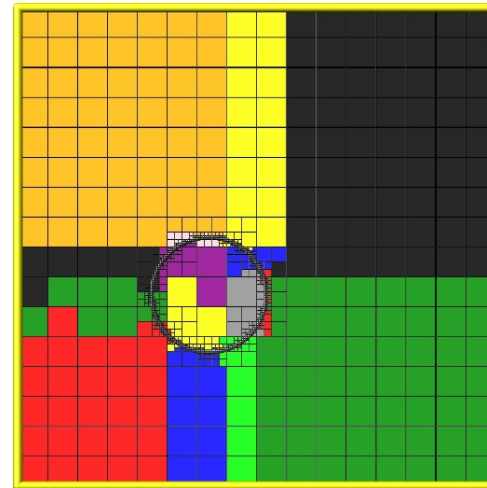
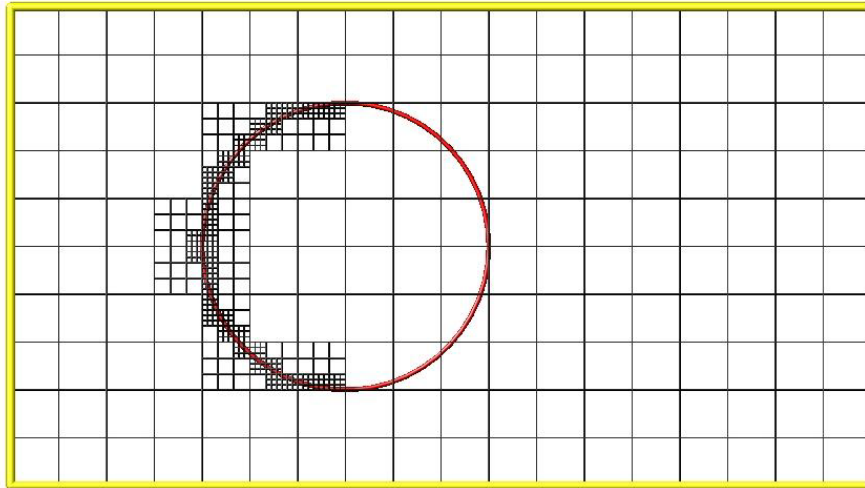
Simulations of Complicated Shapes

- SPARTA now computes all the cut cell volumes, identifies any split cells, colors all grid cells as inside, outside, or cut/split.
- Each surface in a split cell is tagged by which split volume it belongs to, which will be needed for tracking particles into the split cells.
- Infinitely thin surfaces are detected and correctly dealt with during molecular advection.



Adaptive Gridding

- Create/adapt grid in situ, rather than pre-process & read in
- Examples: Generate around surface to user-specified resolution, adapt grid based on flow properties
- Algorithms should be efficient if they require only **local communications**

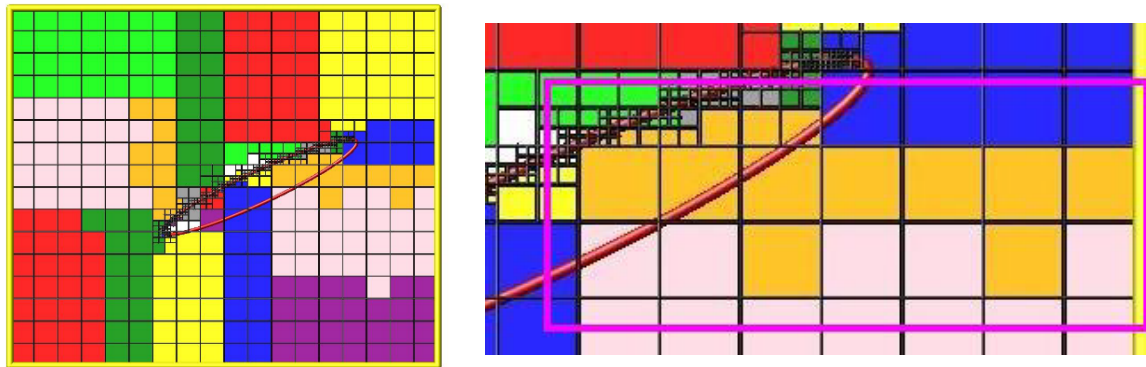


SPARTA

Efficient Communication & Load Balancing

To achieve maximum efficiency:

- **One communication per step**
 - Multiple passes if needed (or can bound molecule move)
- Communication with **modest count of neighbor processors**
- One processor = compact clump of cells via load balancing
 - **Ghost region = nearby cells within user-defined cutoff**
 - Store surface information for ghost cells to complete move



- Balance across processors, **static or dynamic**
- Geometric method: recursive coordinate bisection (RCB)
- **Weighted** by cell count or molecules or CPU

In-situ visualization

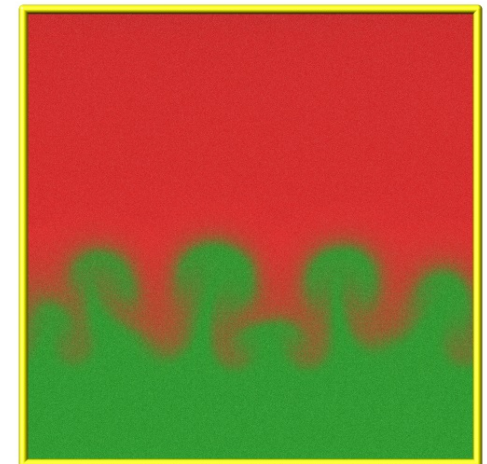
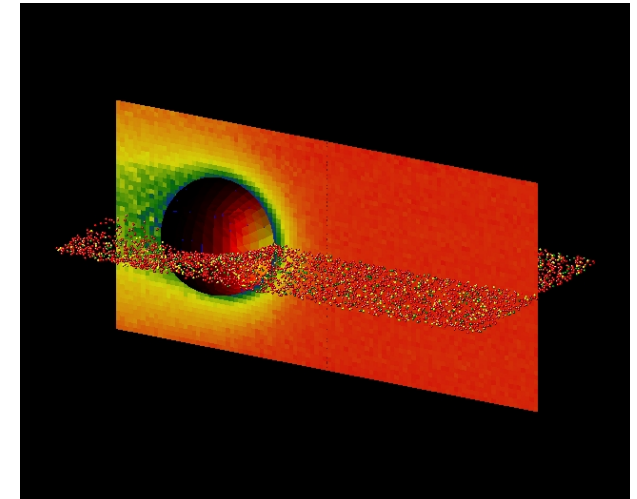
Not a replacement for interactive viz, but ...
Quite useful for **debugging** & quick analysis
At end of simulation (or during), instant movie

Render a JPG snapshot every N time steps:

- Each processor starts with blank image (1024x1024)
- Processor draws its cells/surfaces/molecules with depth-per-pixel
- Merge pairs of images, keep the pixel in front, recurse
- Draw is parallel, merge is logarithmic (like MPI Allreduce)

Images are ray-traced quality

Paraview (<http://www.paraview.org>) has also implemented in-situ.



Benchmarking

Sparta can take advantage of the most advanced computational platforms available

- Flow in a closed box
 - Stress test for communication
 - No preferred communication direction
 - 3D regular grid, 10^4 - 10^{11} (0.1 trillion) grid cells
 - 10 molecules/cell, 10^5 - 10^{12} (1 trillion) molecules
- Effect of threading
 - 2 threads/core = 1.5 speed
 - 4 threads/core = 2x speed

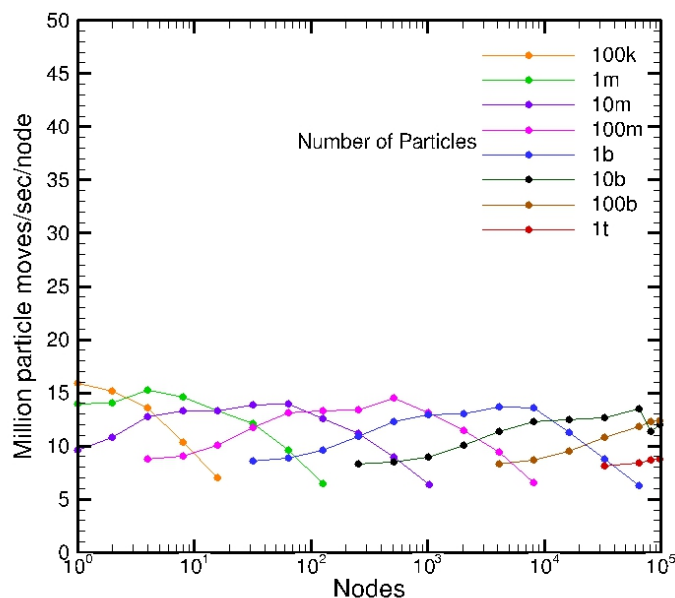


SPARTA

Benchmarking

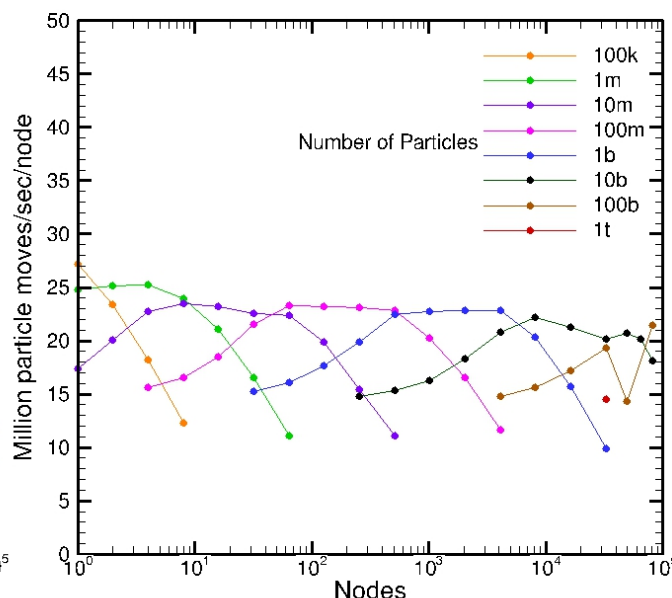
16 cores/node

1 task/core



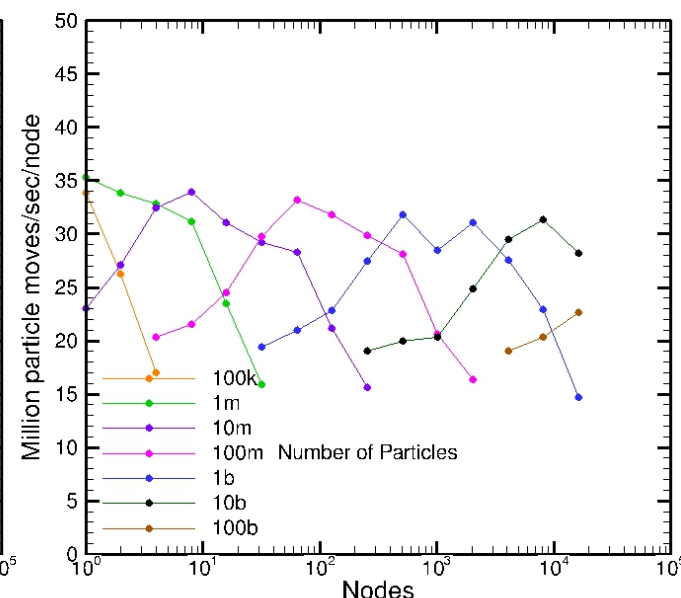
16 cores/node

2 tasks/core



16 cores/node

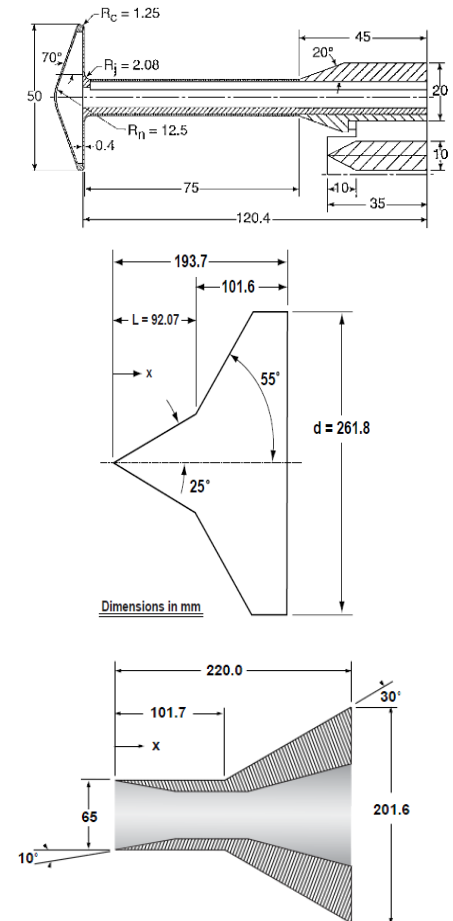
4 tasks/core



- Weak scaling indicates, 10% peak performance reduction from 1 to 10^6 cores
- 2 tasks/core gives 1.5x speedup, 4 tasks/core gives 2x speedup
- A total of **1 trillion molecules** can be simulated on **one third** of the BG/Q
- Maximum number of tasks is 2.6 million

Verification Cases

- **Comparisons with experimental data from:**
 - **SR3**
 - **70° cone (2D-axisymmetric)**
 - **CUBRIC Lens**
 - **25/55° biconic (2D-axisymmetric)**
 - **Hollow cylinder flare (2D-axisymmetric)**

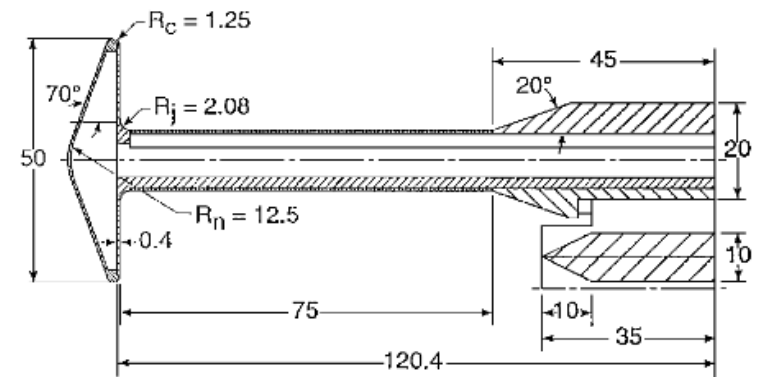


Simulations performed by A. Klothakis and I. Nikolos, *Modeling of Rarefied Hypersonic Flows Using the Massively Parallel DSMC Kernel “SPARTA”*, 8th GRACM International Congress on Computational Mechanics, Volos, Greece, July 12– 15, 2015

SPARTA

Hypersonic Flow around a 70° Blunted Cone

- Geometry: AGARD Group Mars Pathfinder
- Flow-field dimensions: 10 cm x 15 cm
- Grid: 600 x 600 cells, 2-level 10 x 10 cells around the cone area



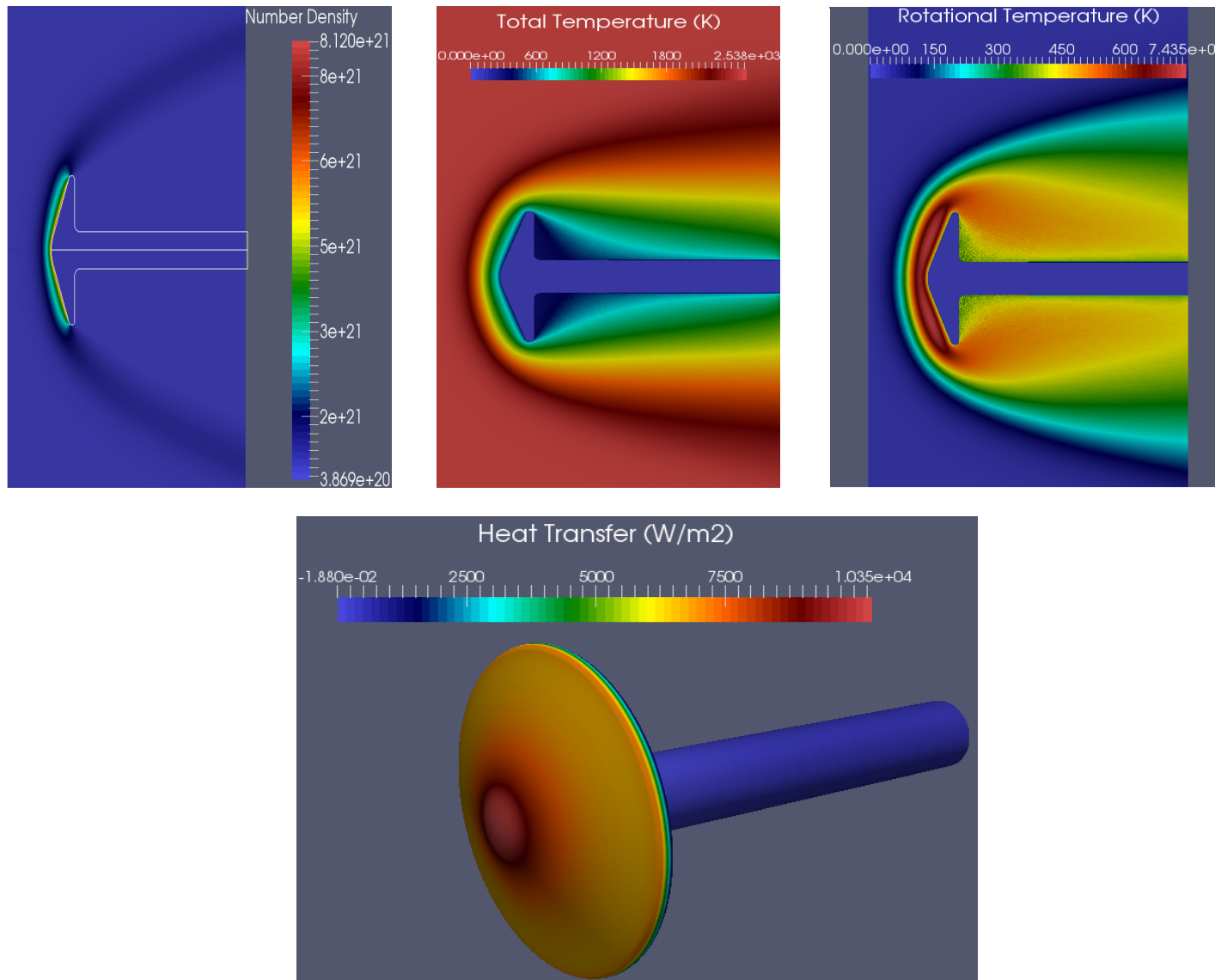
Blunt cone geometry
(Dimensions in mm)

Flow conditions	Gas	Ma	T_0	P_0	Re
1	N ₂	20.2	1100	3.5	1420
2	N ₂	20	1100	10	4175

Allègre, J., Bisch, D., Lengrand, J. C. (1997), “Experimental Rarefied Heat Transfer at Hypersonic Conditions over a 70-Degree Blunted Cone”, *Journal of Spacecraft and Rockets*, Vol. 34, No. 6, pp. 724-728.

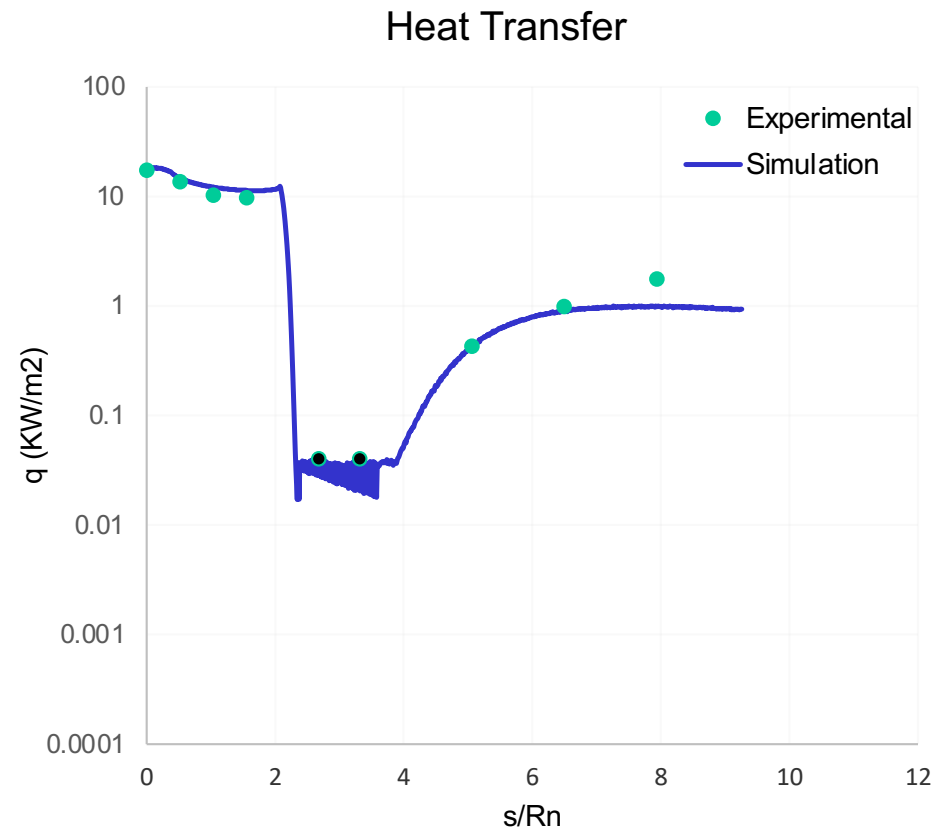
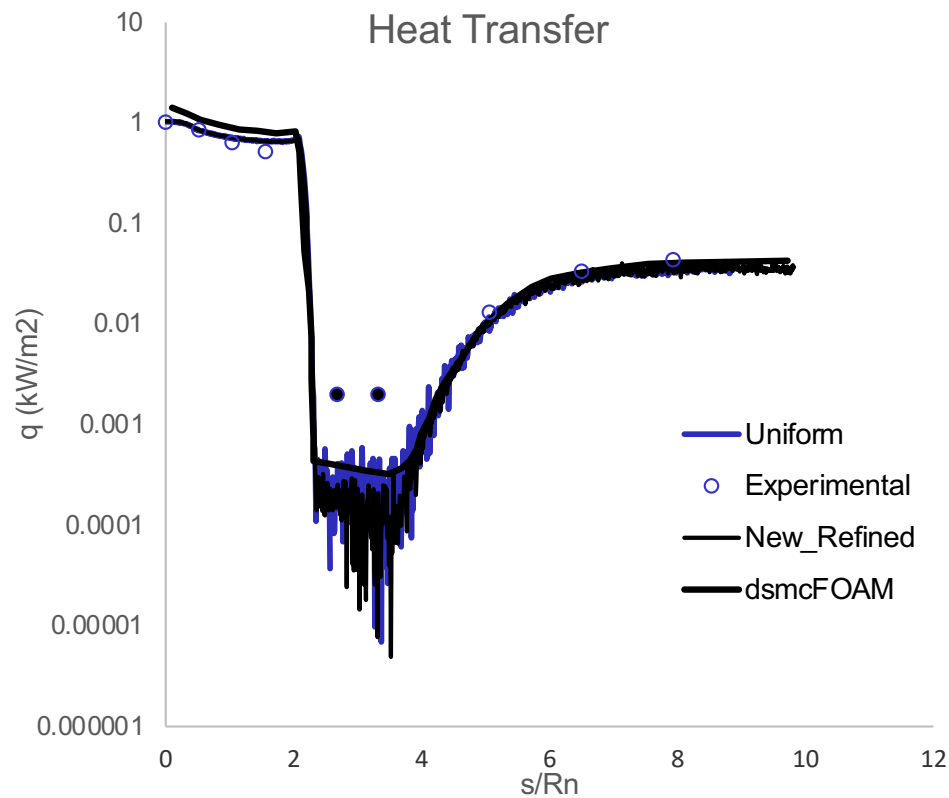
SPARTA

Hypersonic Flow around a 70° Blunted Cone



SPARTA

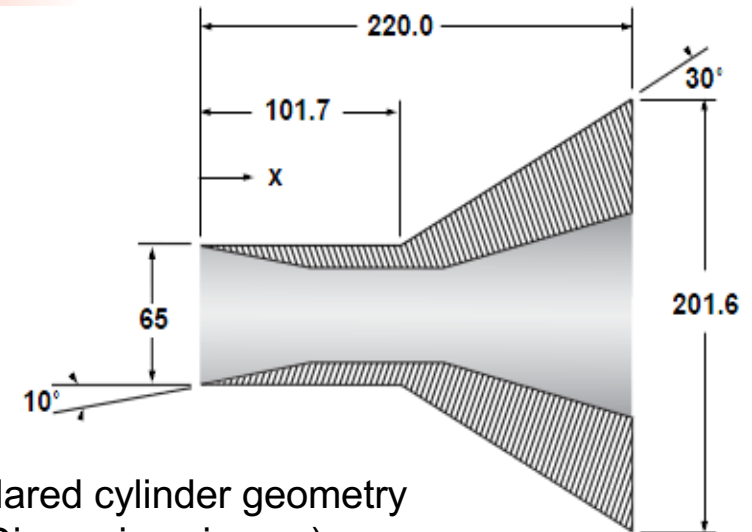
Hypersonic Flow around a 70° Blunted Cone



SPARTA

Hypersonic Flow around a Flared Cylinder

- Flow-field dimensions: 22 cm x 12 cm
- Grids: Uniform 1000 x 1800 cells,
2-Level 957 x 440 cells second level
10x10 cells



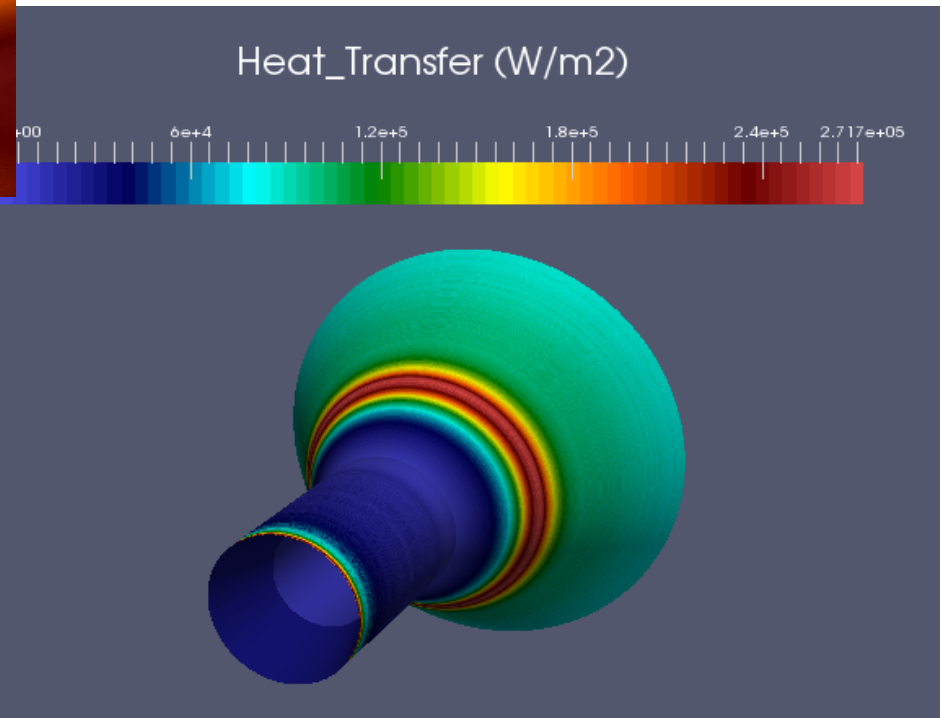
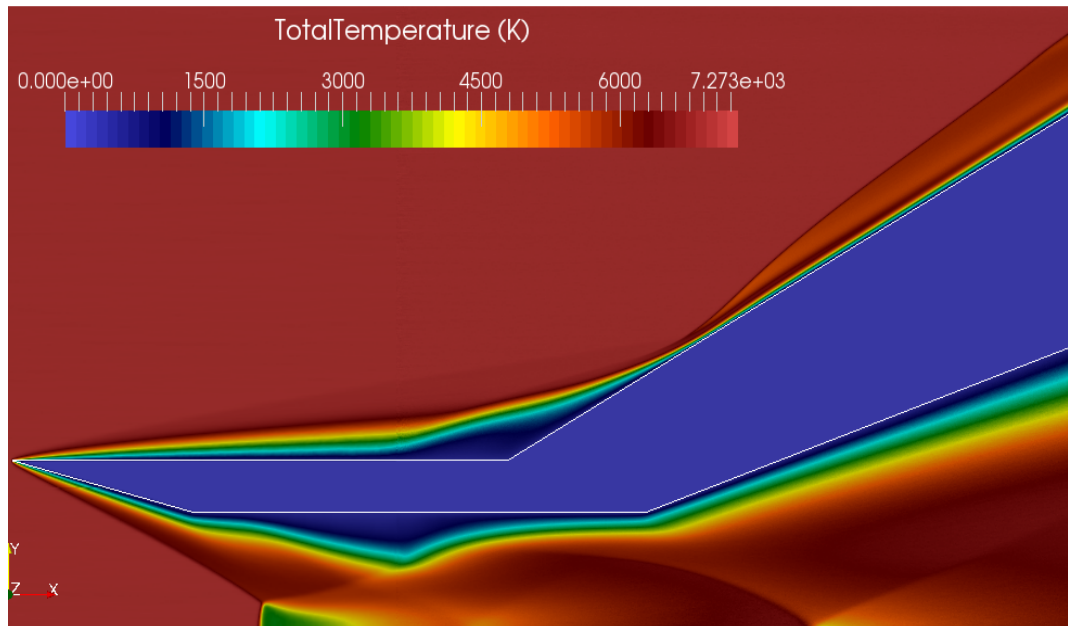
Flared cylinder geometry
(Dimensions in mm)

Conditions	Flow Velocity (m/s)	Number Density (m ⁻³)	Flow Temperature (K)	Gas	Surface Temperature (K)
LENS Run 11	2484	3.78x10 ²¹	95.6	N ₂	297.2

Holden, M., Harvey, J., Wadhams, T., and MacLean, M., "A Review of Experimental Studies with the Double Cone Configuration in the LENS Hypervelocity Tunnels and Comparisons with Navier-Stokes and DSMC Computations," AIAA 2010-1281, 48th AIAA Aerospace Sciences Meeting, Orlando, FL, January 4-7, 2010.

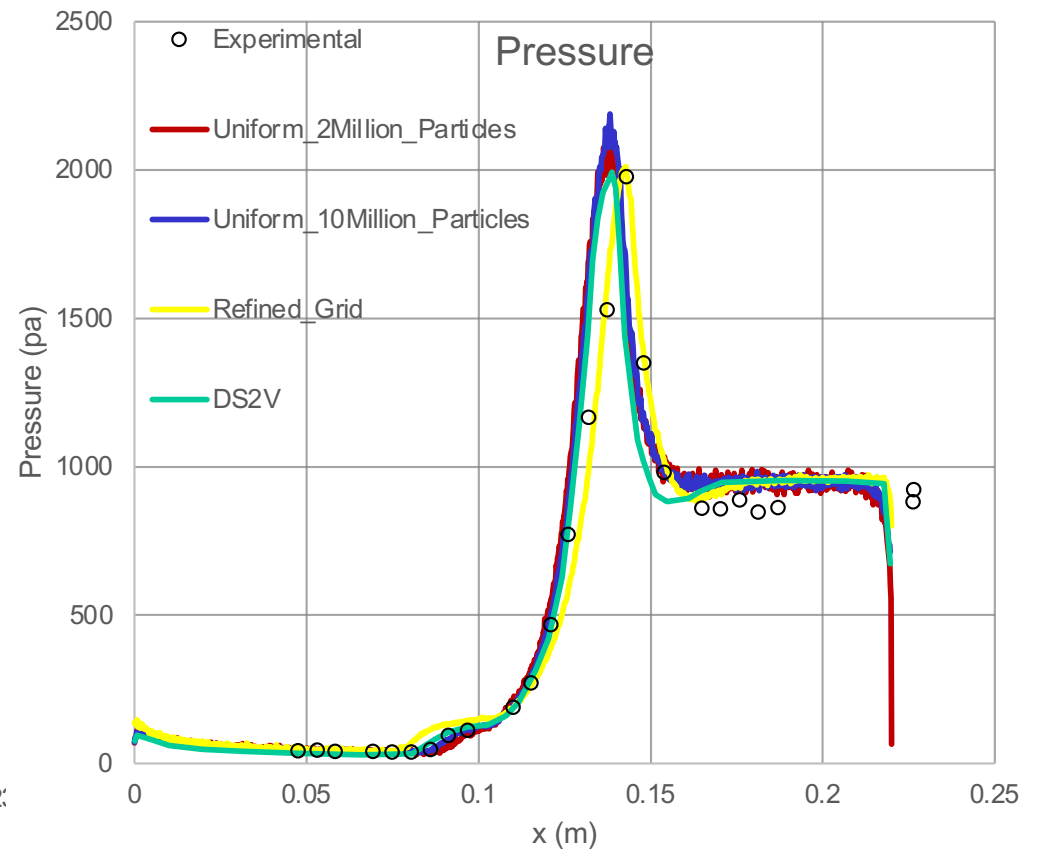
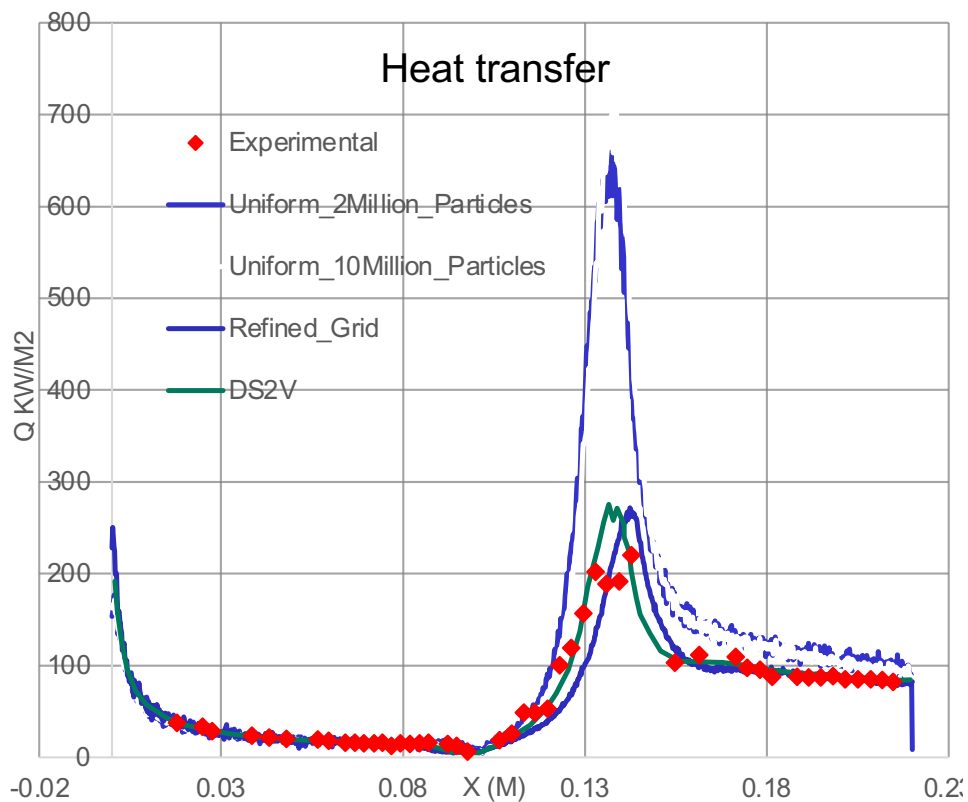
SPARTA

Hypersonic Flow around a Flared Cylinder



SPARTA

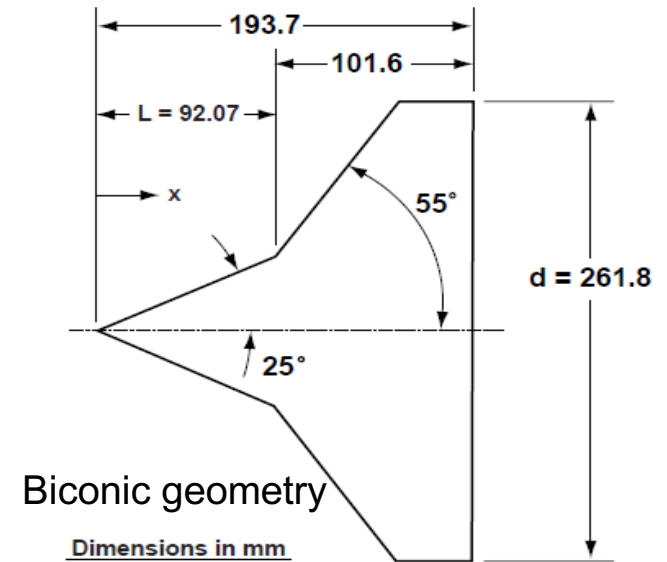
Hypersonic Flow around a Flared Cylinder



SPARTA

Hypersonic Flow around a 25/55° Biconic

- Flow-field dimensions: 22 cm x 50 cm
- Grid: 2 level grid, first level 870 x 870 cells, second level 10 x 10 cells refinement of the first level, second level starts from 5 cm after the biconic's leading edge and ends at the end of the biconic's surface.

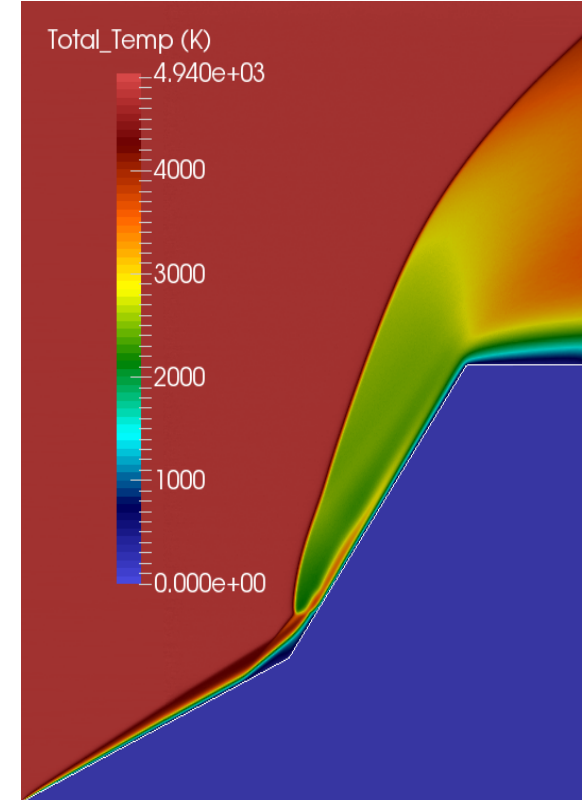
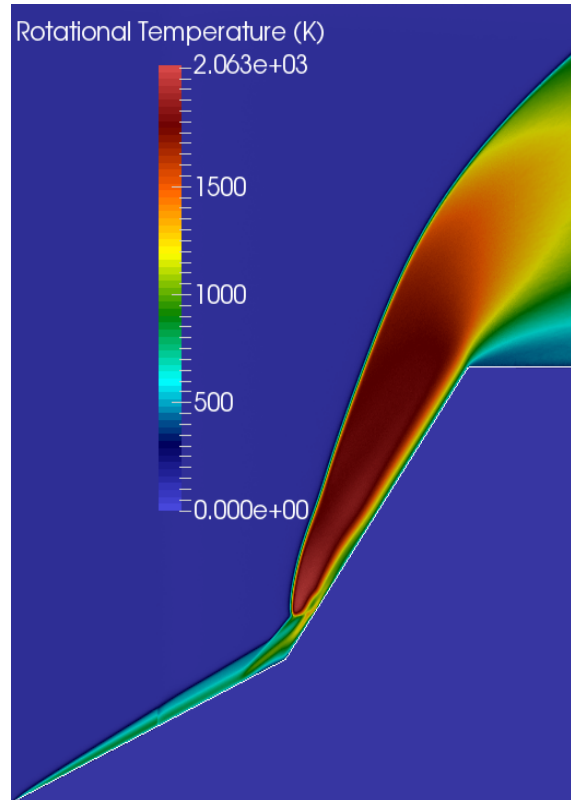
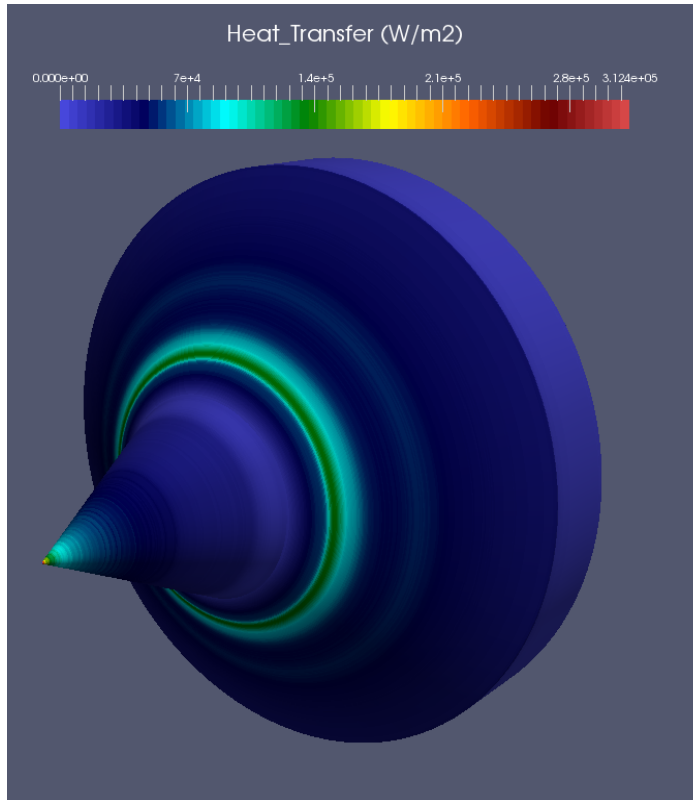


Conditions	Flow Velocity (m/s)	Number Density (m ⁻³)	Flow Temperature (K)	Gas	Surface Temperature (K)
CUBRC Run 7	2072.6	3.0x10 ¹⁸	42.61	N ₂	297.2

Holden, M., Harvey, J., Wadhams, T., and MacLean, M., "A Review of Experimental Studies with the Double Cone Configuration in the LENS Hypervelocity Tunnels and Comparisons with Navier-Stokes and DSMC Computations," AIAA 2010-1281, 48th AIAA Aerospace Sciences Meeting, Orlando, FL, January 4-7, 2010.

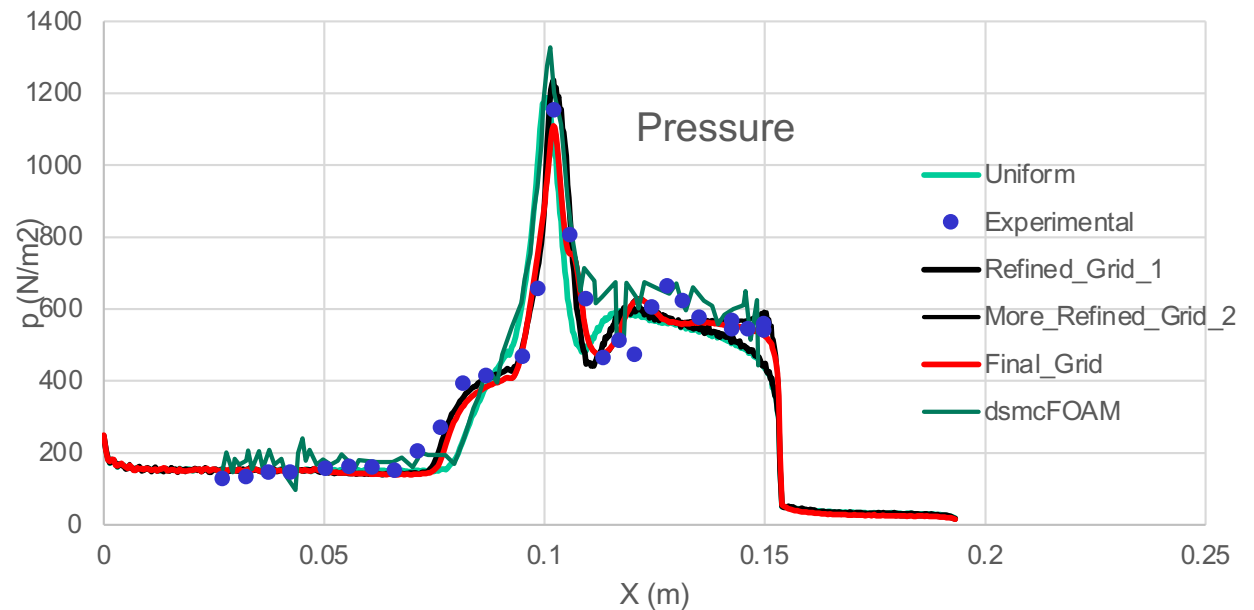
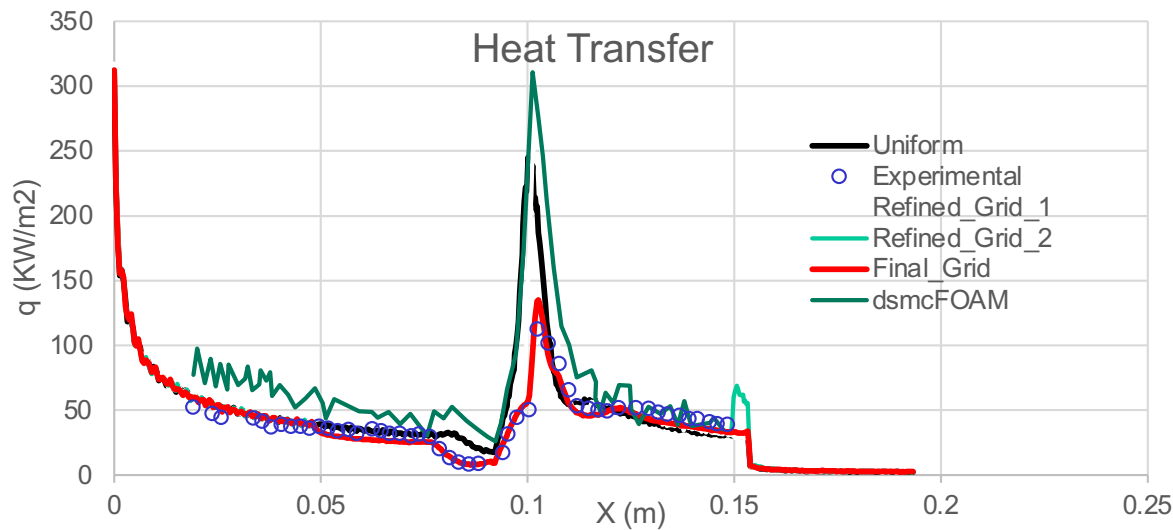
SPARTA

Hypersonic Flow around a 25/55° Biconic



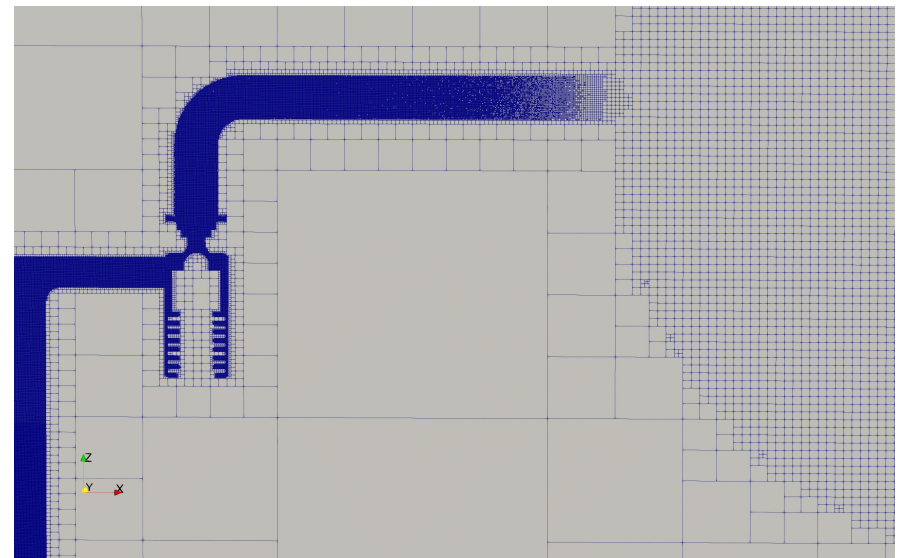
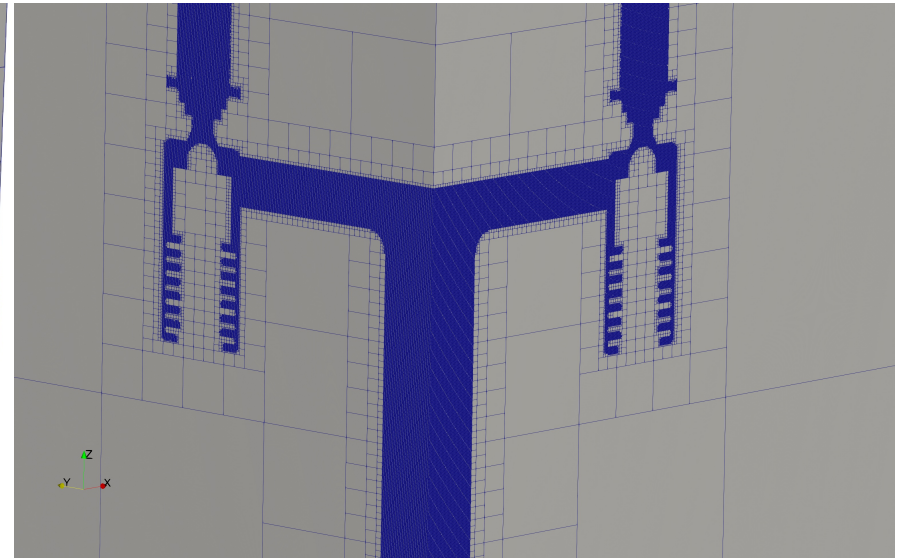
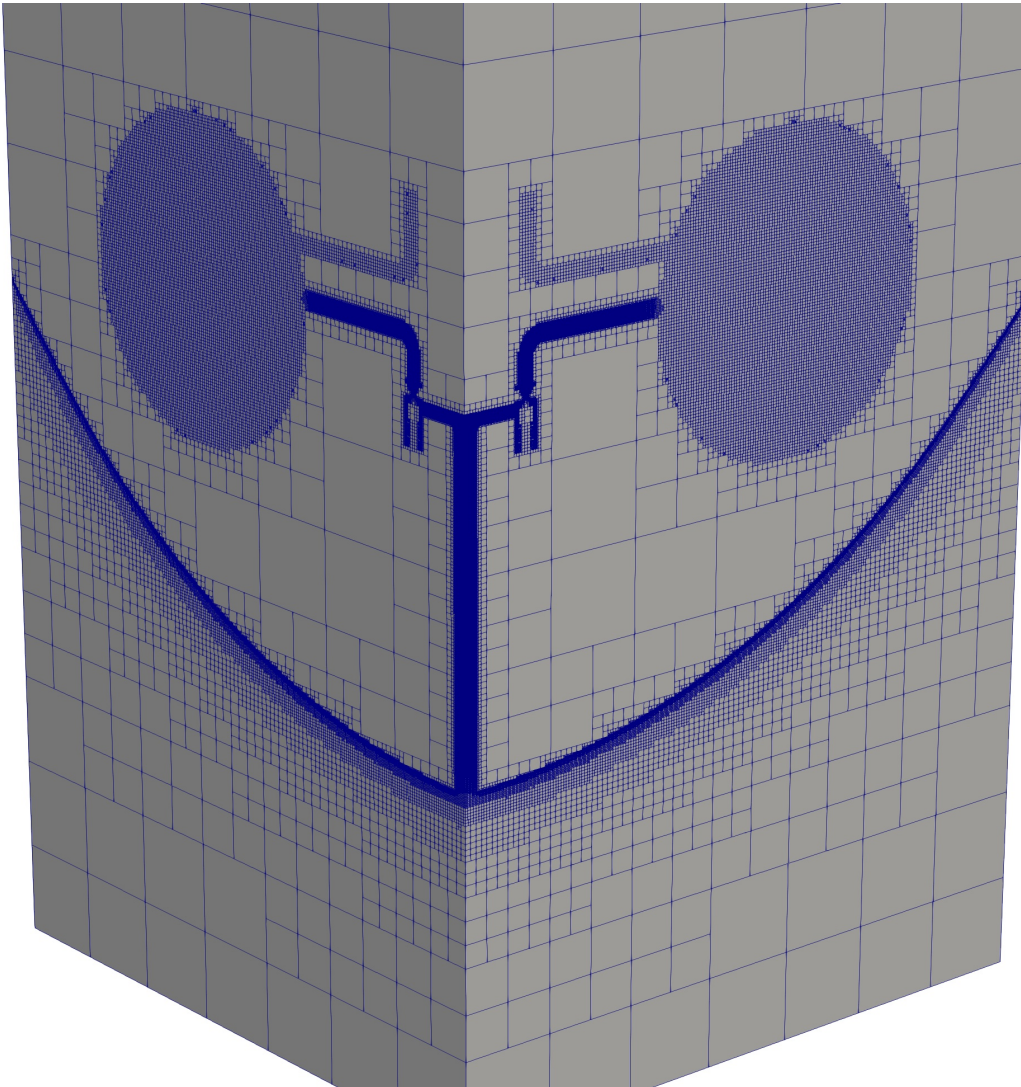
SPARTA

Hypersonic Flow around a 25/55° Biconic



Computational Grid

“Flight-like” sampling geometry



DSMC Numerical Error

Numerical error

Four parameters control DSMC numerical error:

- Sample size per cell (M_c)
 - Simulators per cell (N_c)
 - Cell size (Δx)
 - Time step (Δt)
- statistical error
- discretization error

Early DSMC users followed rule-of-thumb guidelines:

- Sample enough to drive statistical error down
- Keep time step smaller than $\sim 1/4$ mean collision time
- Keep cell size smaller than $\sim 1/3$ mean free path
- Use a minimum of ~ 20 simulators per cell

This leads to an error of $\sim 2\%$

Functional Form of Error

Numerical error

Functional form that represents DSMC data

- Taylor series expansion in Δx , Δt , and $1/N_c$
- Retain statistically significant terms:

$$\frac{K_{DSMC}}{K} = 1.0001 + 0.0286 \left(\frac{\Delta t}{t_o} \right)^2 + 0.0411 \left(\frac{\Delta x}{\lambda} \right)^2 - 0.01 \left(\frac{\Delta t}{t_o} \right)^2 \left(\frac{\Delta x}{\lambda} \right)^2 - 0.147 \frac{1}{N_c} + \frac{1}{N_c} F \left[\frac{\Delta t}{t_o}, \frac{\Delta x}{\lambda}, \left(\frac{\Delta t}{t_o} \right)^2 \right]$$

Simulation Discretization Error

Numerical error

- Trace species (noble gases) do not participate in chemical reactions.
- Primary concern is the concentrations of noble gases (mass is one of the three collisional invariants of DSMC).
- Coarse calculations can capture this quantity, but not all of quantities of interest:
 - Flow and heating rates are subject to capturing the transport properties.
- For our case, spatial and temporal discretization errors have been minimized
- Number of simulators per cell remains a source of concern.
- Error of DSMC simulations needs to be understood and accurately predicted for DSMC to be used as an “honest broker” in the question whether this concept is feasible.
- Simulations are not “discovery” simulations, but engineering design.
- **Initial estimates as well as final results suggest ~ 4% total discretization error in simulations.**

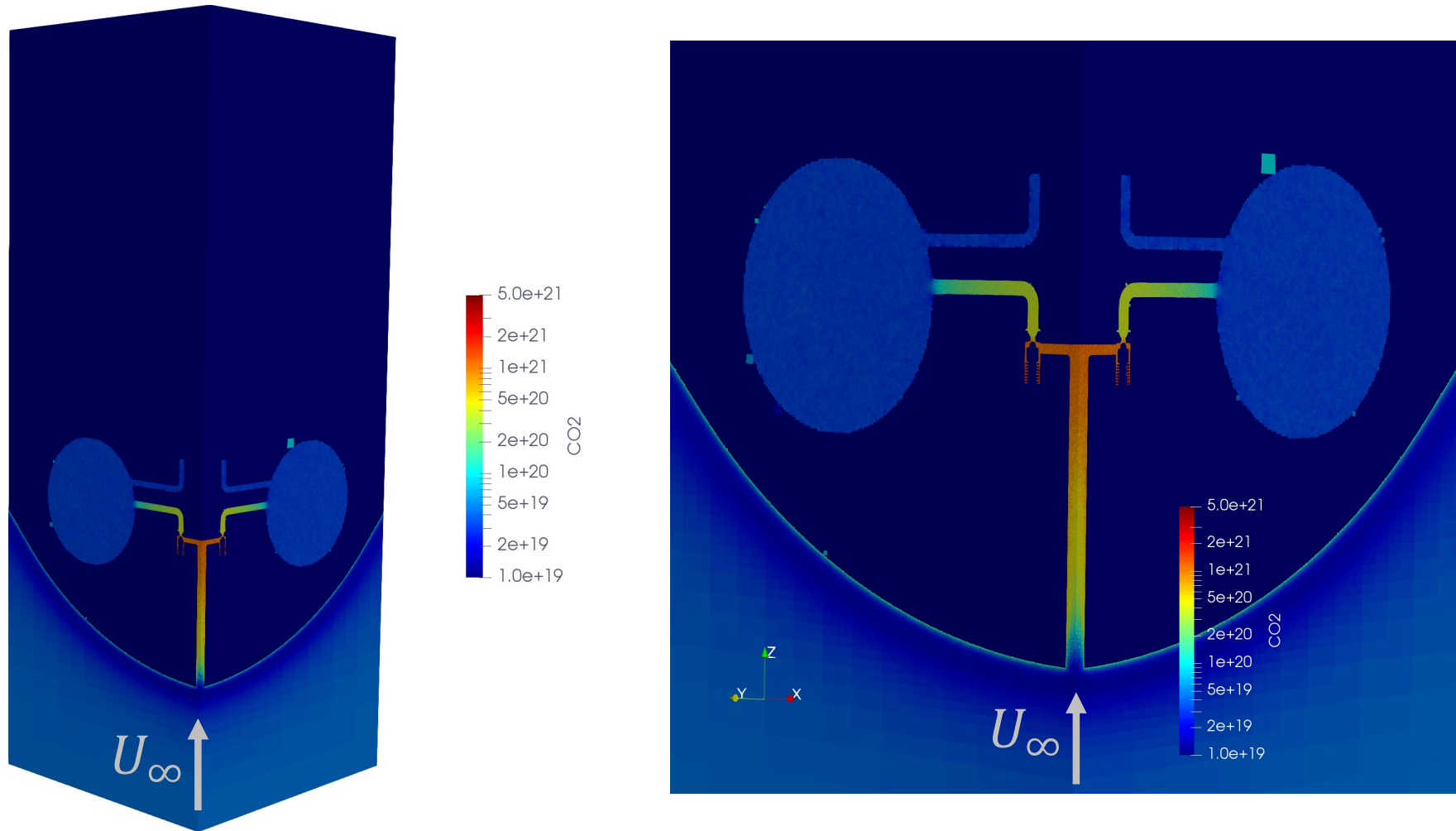
Two cases examined

Additional cases planned for future simulations

- Nominal flight
- Perturbed flight path (5 deg AoA)
- Free Stream Conditions:
 - $U_{\infty} = 10.5 \text{ km/s}$
 - $T_{\infty} = 196 \text{ K}$
 - $P_{\infty} \cong 0.14 \text{ Pa}$
 - $X_{CO_2} \cong 0.92, X_{N_2} \cong 0.033$
 - $X_{40Ar} = X_{36Ar} = X_{4He} = X_{20Ne} = 0.01$
 - $X_{132Xe} = X_{128Xe} = X_{3He} = X_{22Ne} = X_{80Kr} = X_{84Kr} = 0.001$
 - $\lambda_{\infty} \cong 0.05 \text{ m}$

Nominal Flight (Quarter Geometry)

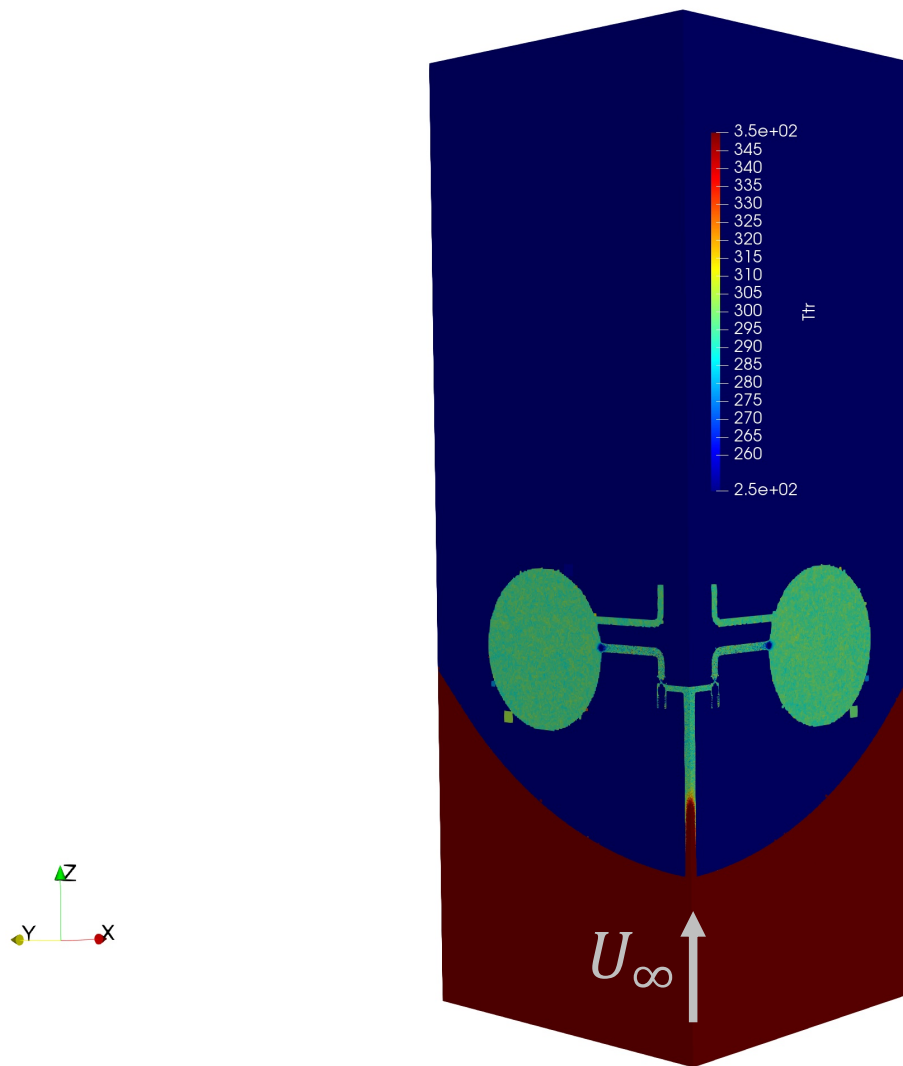
0° AoA, nominal free stream conditions



CO₂ Number density

Nominal Flight (Quarter Geometry)

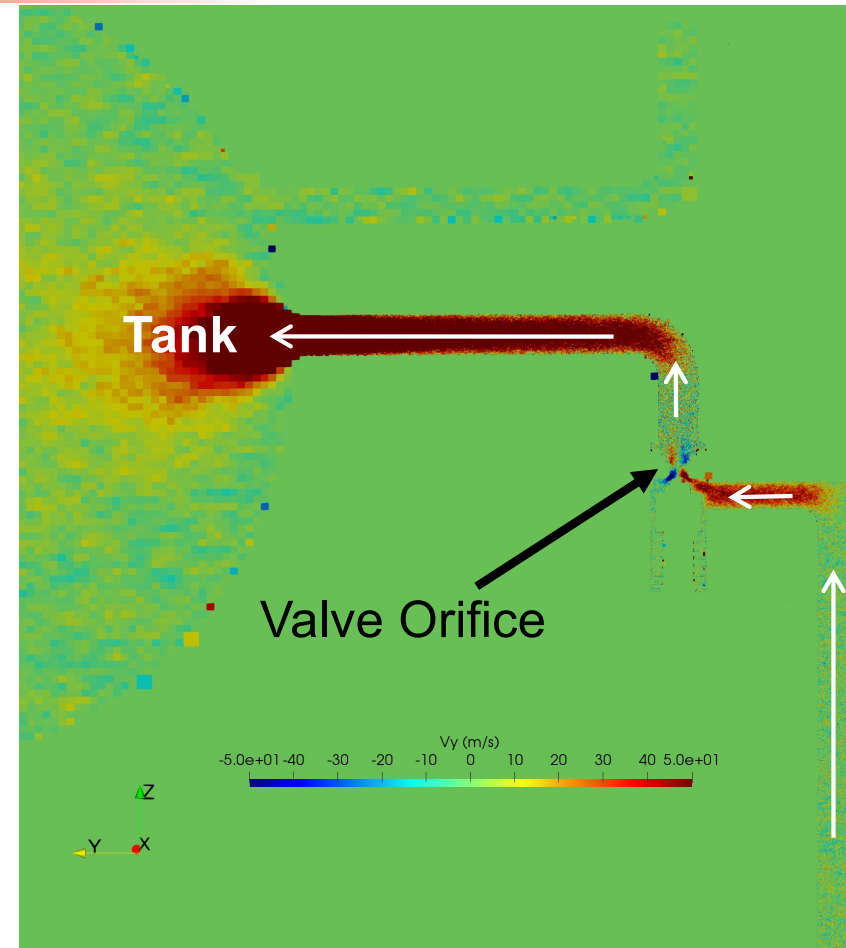
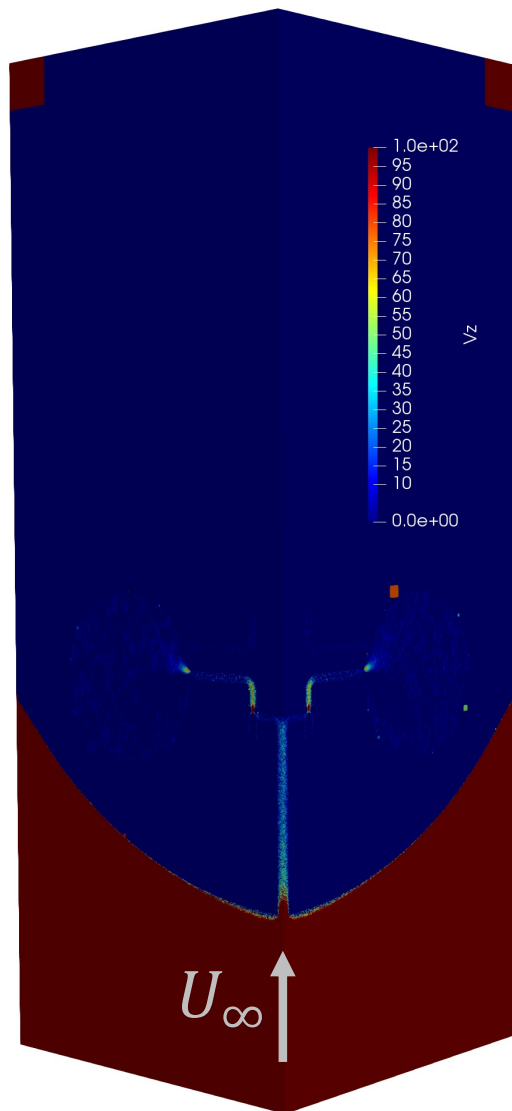
0° AoA, nominal free stream conditions



Surfaces are assumed to be diffuse and isothermal

Nominal Flight Velocity profiles

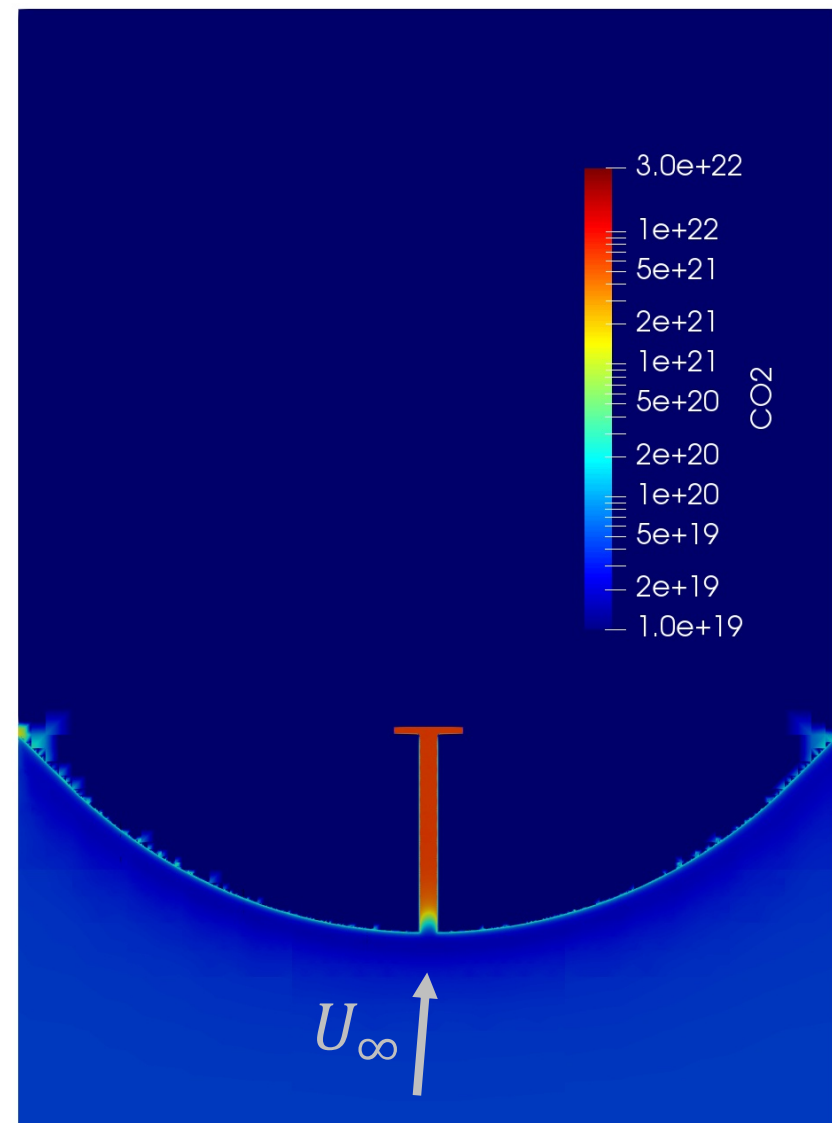
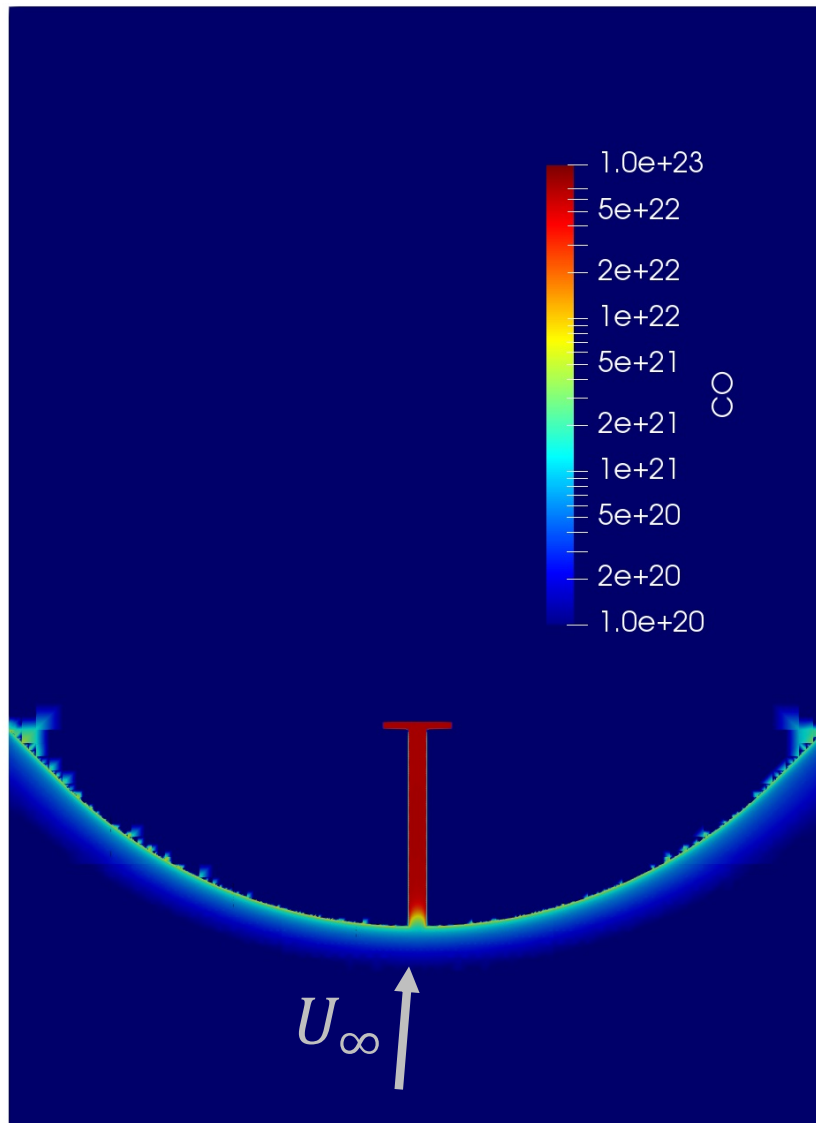
Internal flow → through the valve and into the tank



Flow is slows down inside the tube and accelerates during the expansion to the tanks

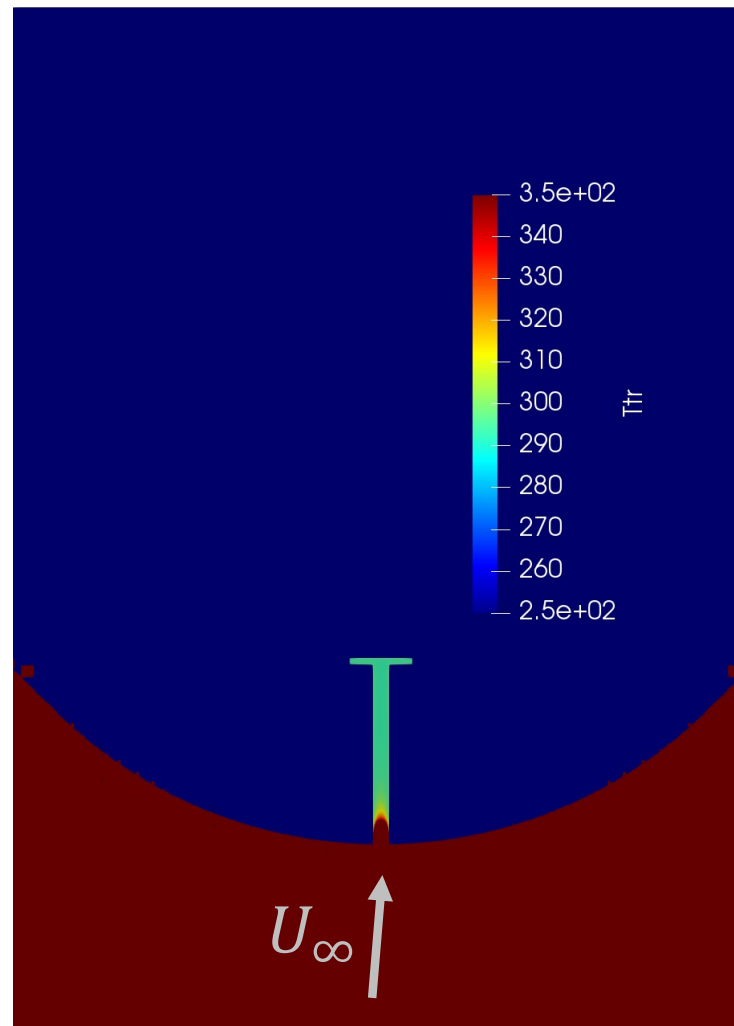
Off-Nominal Flight Condition

5° AoA



Off-Nominal Flight Condition

5° AoA



Flow reaches surface temperature in the tube.

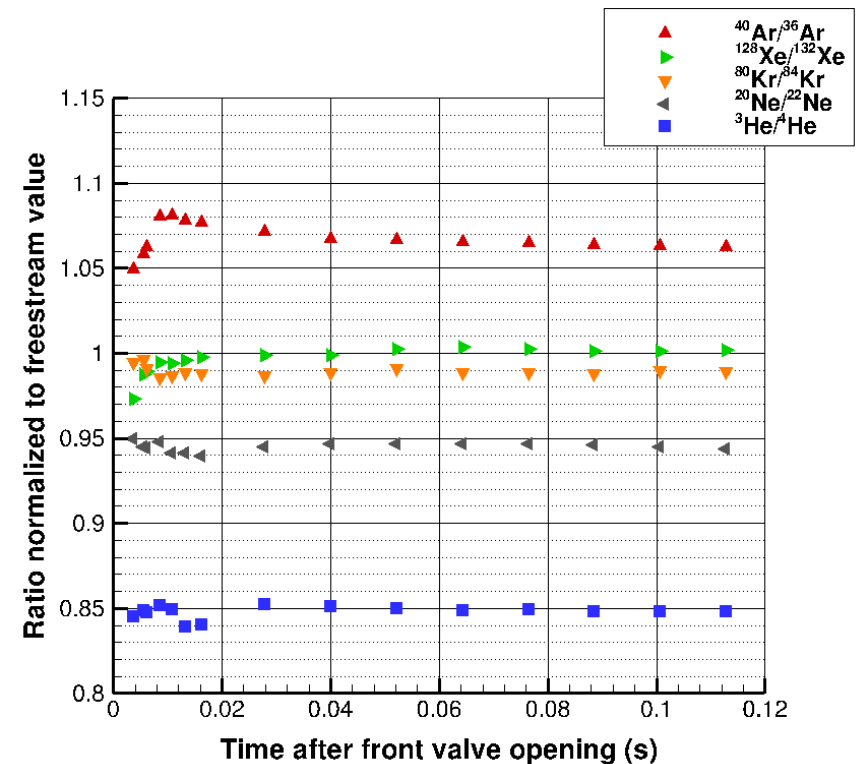
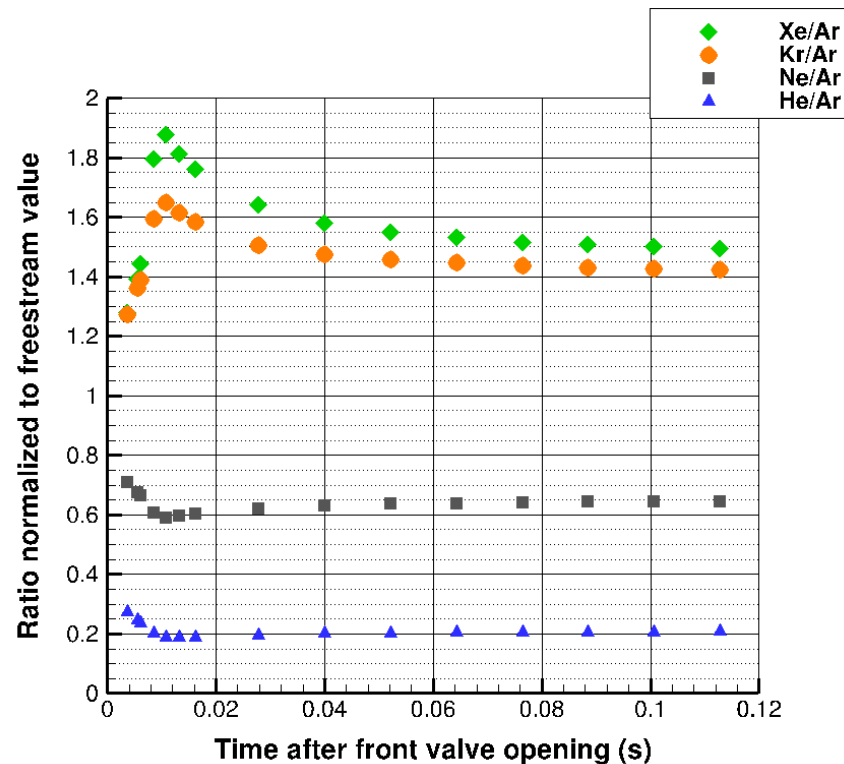
Summary

Simulation Work

- DSMC/SPARTA was employed to demonstrate the feasibility of the concept.
- Simulation Challenges:
 - **Simulations required 10,000-20,000 cores for over a month of run time (with an exascale code!).**
 - In many occasions, simulations push the limit of computer science.
 - Although the individual models employed (molecular, energy exchange, chemistry) have been verified and validated, there is no comprehensive experimental measurement available.
 - **Simulation discretization error is estimated to 4%.**

Elemental and Isotopic Ratios in the Tank (best run)

Quantifying fractionation

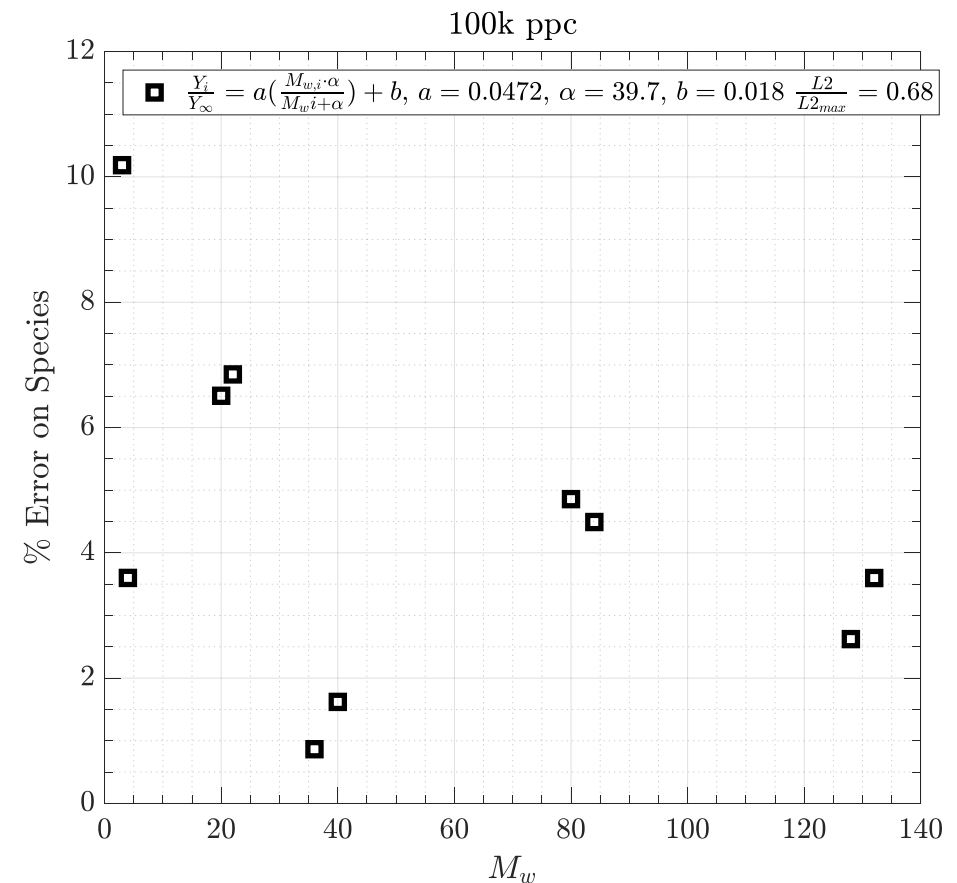
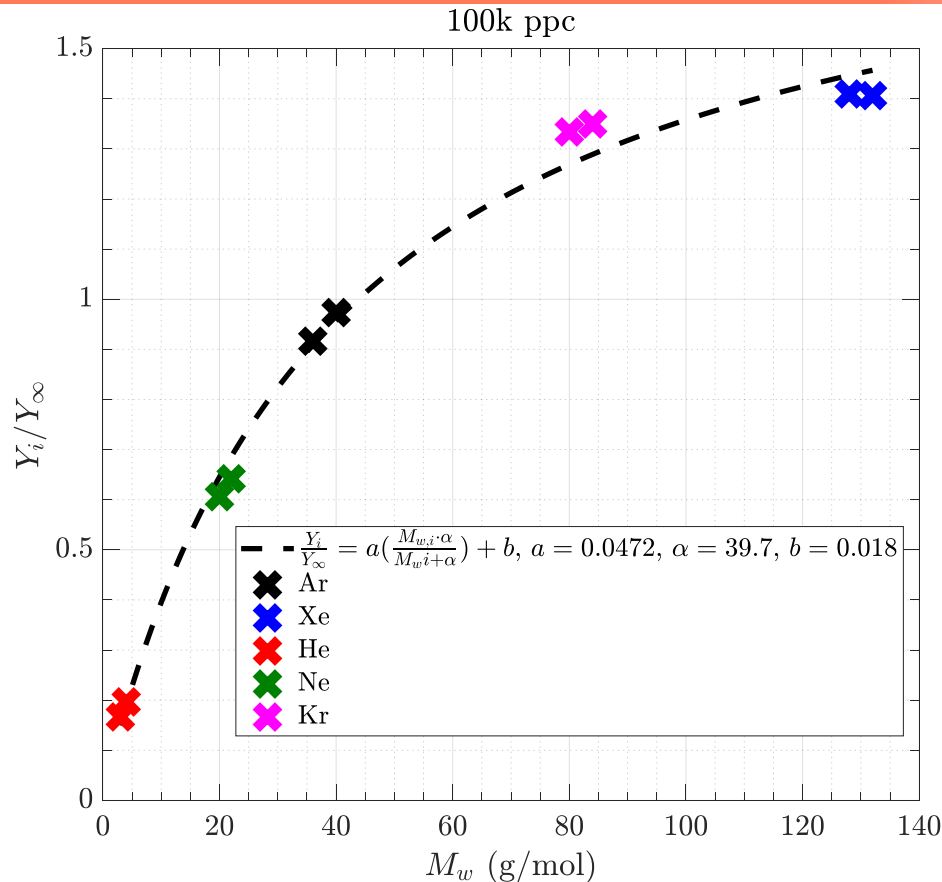


Current observations:

- Fractionation does occur, and is driven by molecular weight differences (heavier species are preferentially sampled compared to lighter species)
 - This is consistent for the isotopic ratios (heavier species/light species in the right plot), and elemental fractionation (left plot)
- Note that these results are still only after a short amount of time sampling

Mass Dependent Fractionation (best run)

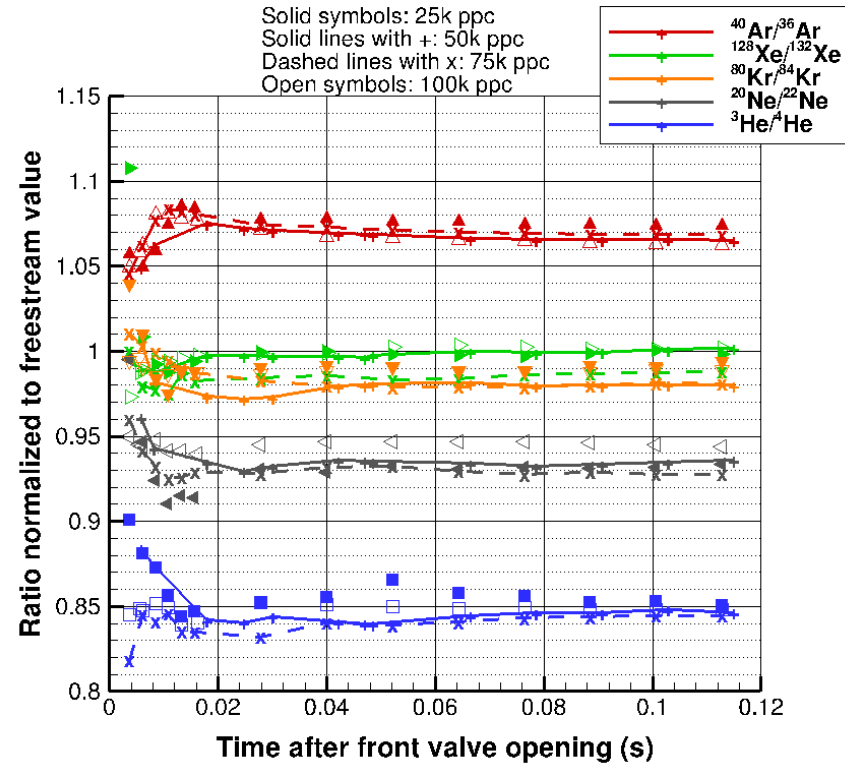
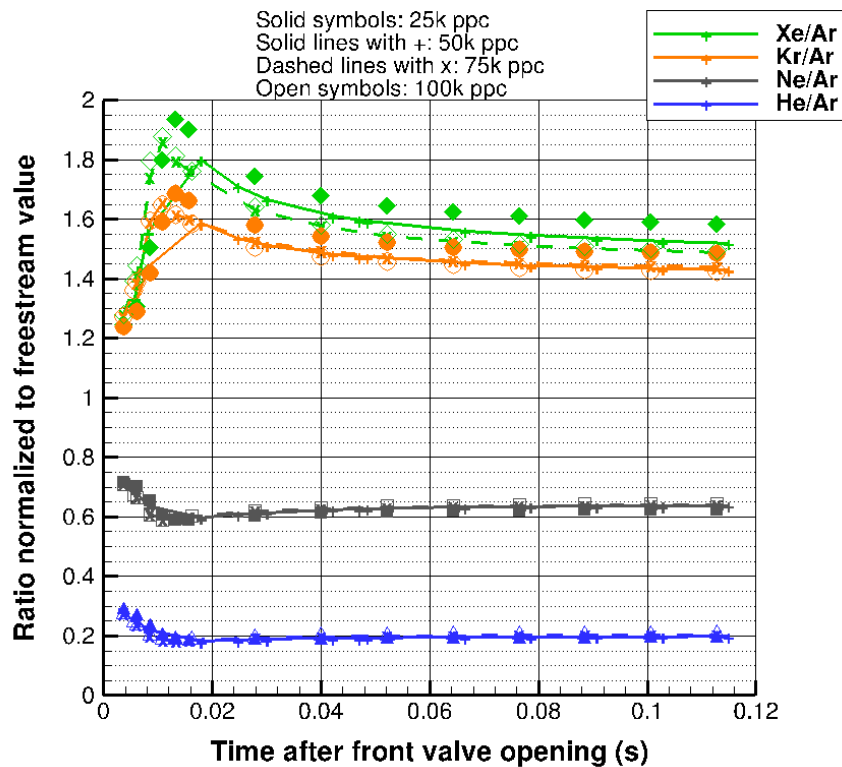
Fitting numerical results



Comments:

- Simulation results are fit as a function of reduced molecular weight – alpha is a fitting parameter determined using a non-linear fitting algorithm (Levenberg-Marquardt)
- Mass-dependent transport through the system is reasonably re-produced with the fit
- alpha = 39.7 g/mol is characteristic of the free stream Mw → discussed later

Elemental and Isotopic Ratios in the Tank (comparison between different number of initial particles)



Error with respect
to 100k ppc case

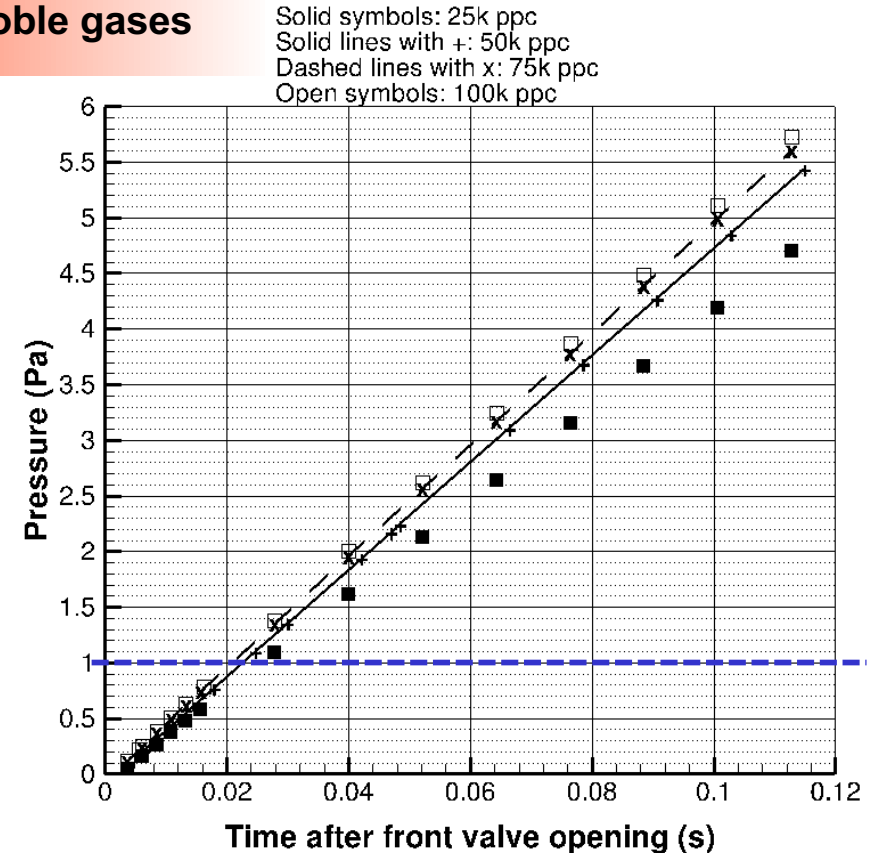
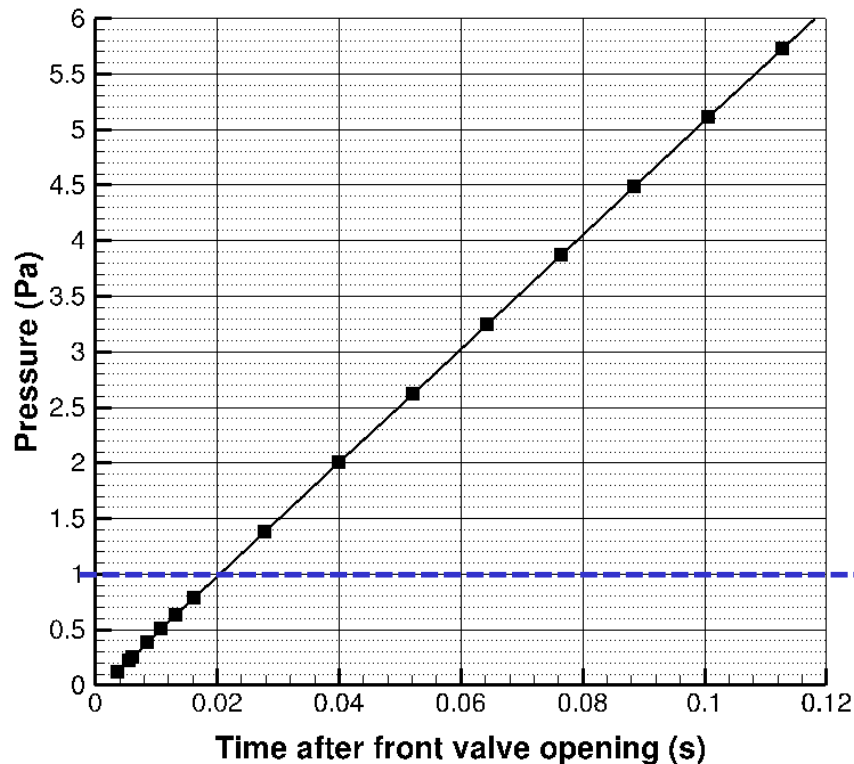
case	$^{40}\text{Ar}/^{36}\text{Ar}$	$^{128}\text{Xe}/^{132}\text{Xe}$	$^{80}\text{Kr}/^{84}\text{Kr}$	$^{20}\text{Ne}/^{22}\text{Ne}$	$^3\text{He}/^4\text{He}$	Xe/Ar	Kr/Ar	Ne/Ar	He/Ar
75	-0.58%	1.42%	0.72%	1.74%	0.34%	0.07%	-1.36%	0.76%	0.80%
50	-0.28%	0.03%	0.83%	0.87%	0.15%	-2.02%	-0.74%	1.03%	3.52%
25	-0.99%	0.35%	-0.75%	1.04%	-0.47%	-5.93%	-4.21%	3.15%	8.35%

Comments:

- Some sensitivity to initial number of particles, especially for heavier noble gases and isotopes ratios
- However, there is convergence when number of ppc increases towards 100k.

Sample Acquisition Tank Pressure

Objective is to acquire $\sim 5 \cdot 10^{-7}$ torr partial pressure of noble gases

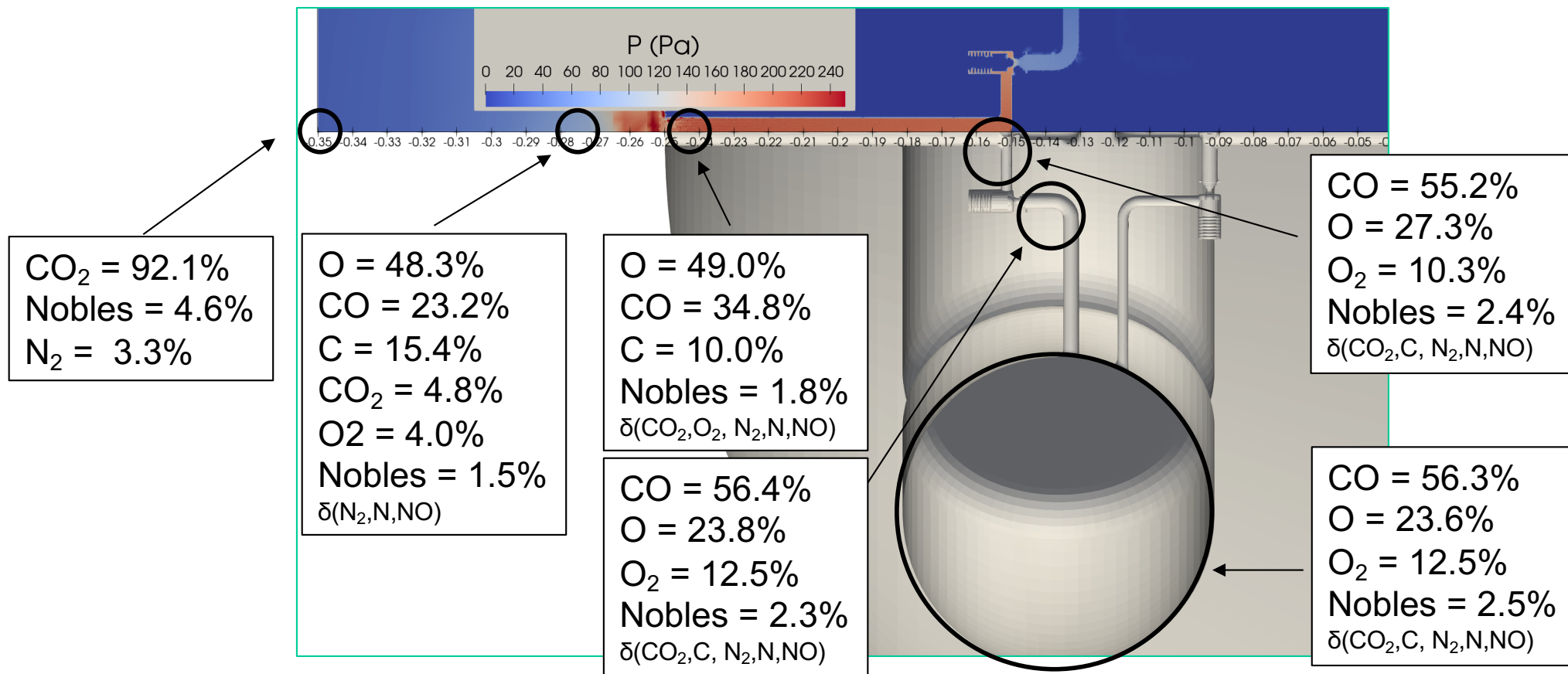


Comments:

- All simulation results have shown a linear pressure rise in the tank at early times
- 1 Pa of tank pressure is our current estimate to the amount of sample required for optimal QITMS measurements
- 25k ppc run underestimates pressure rise by 17% compared to 100k ppc.
- The opening/closing time of the Mindrum valve has been shown to be < 0.002 s

Variation of mole fractions along stagnation line

Fractionation through the sampling system

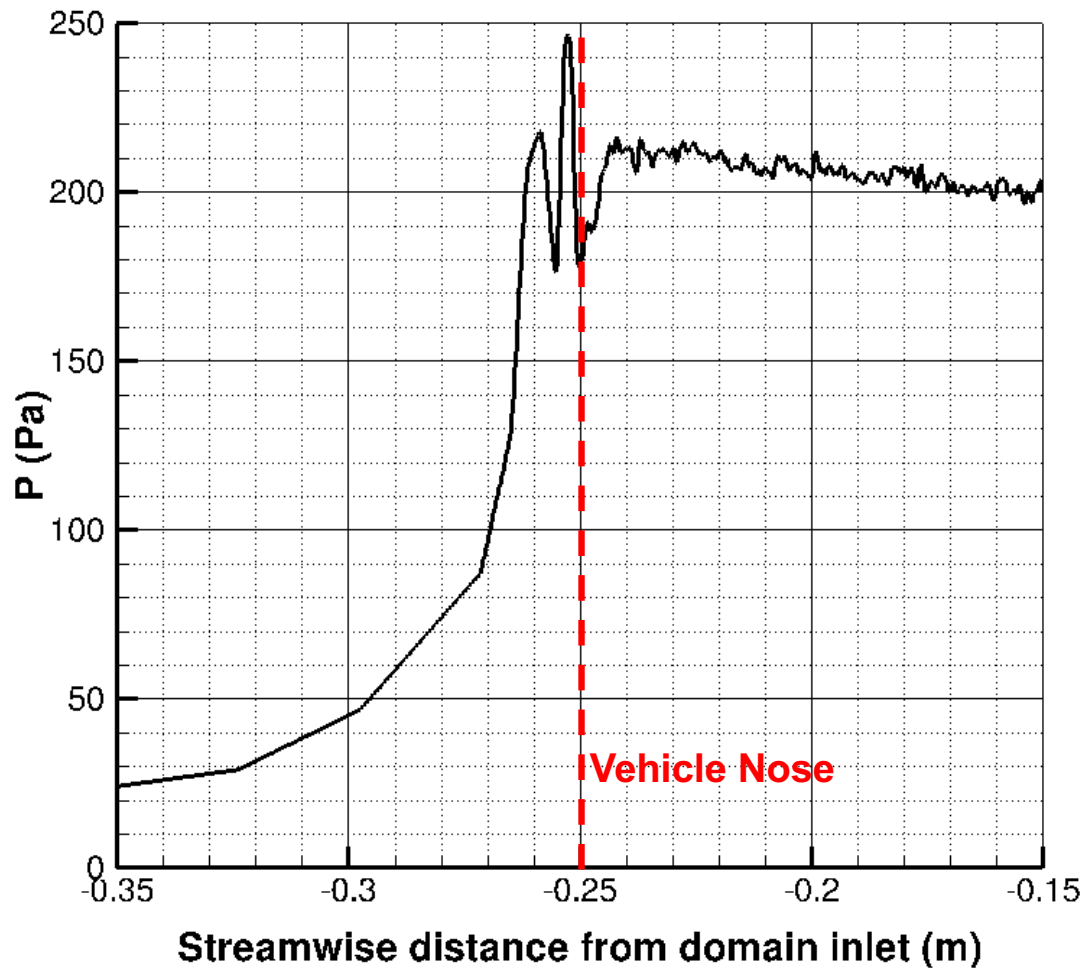


Comments:

- Strong variations in species mole fractions along stagnation line:
 - Largest variation across bow shock
 - Recombination into molecules as flow cools down
 - Close to freezing of flow from 1st bend until sampling tank: minimal effect of valve on non-nobles

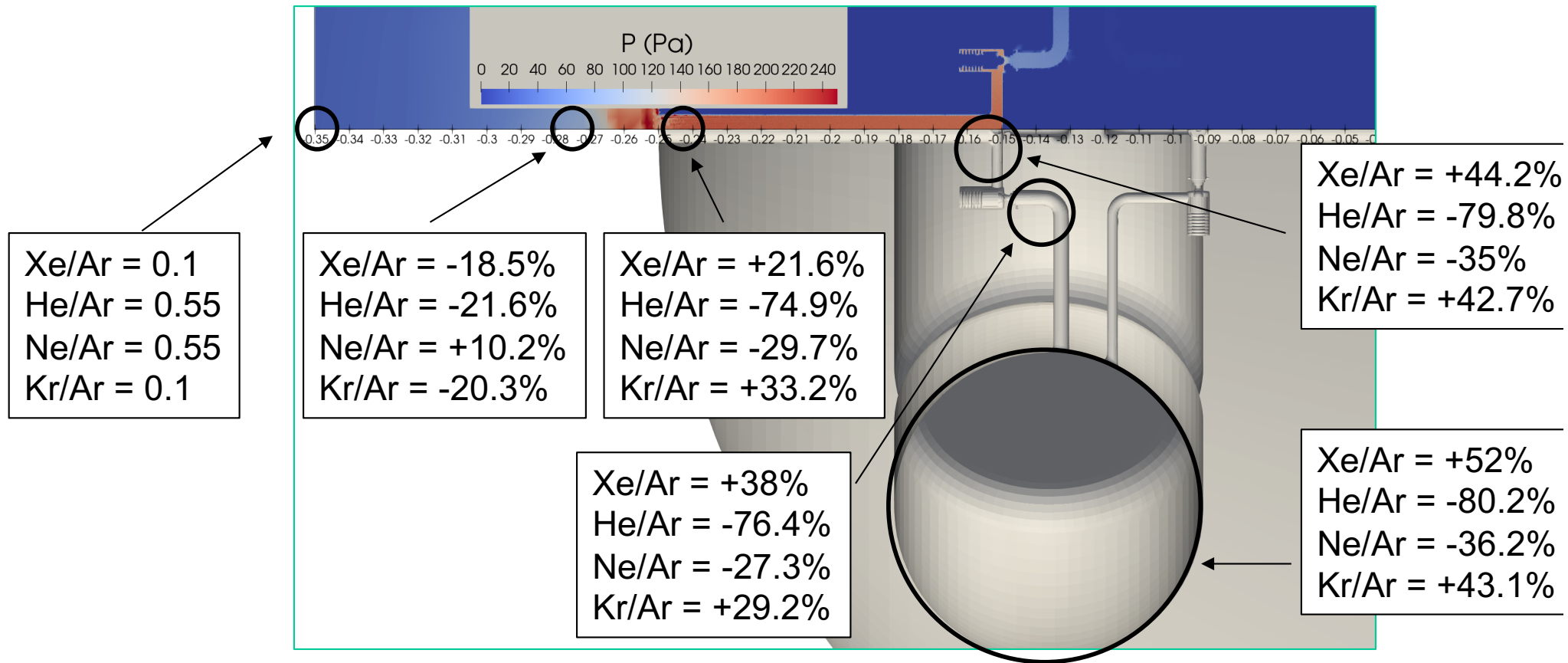
Variation of mole fractions along stagnation line

Fractionation through the sampling system



Variation of elemental ratios along stagnation line

Fractionation through the sampling system

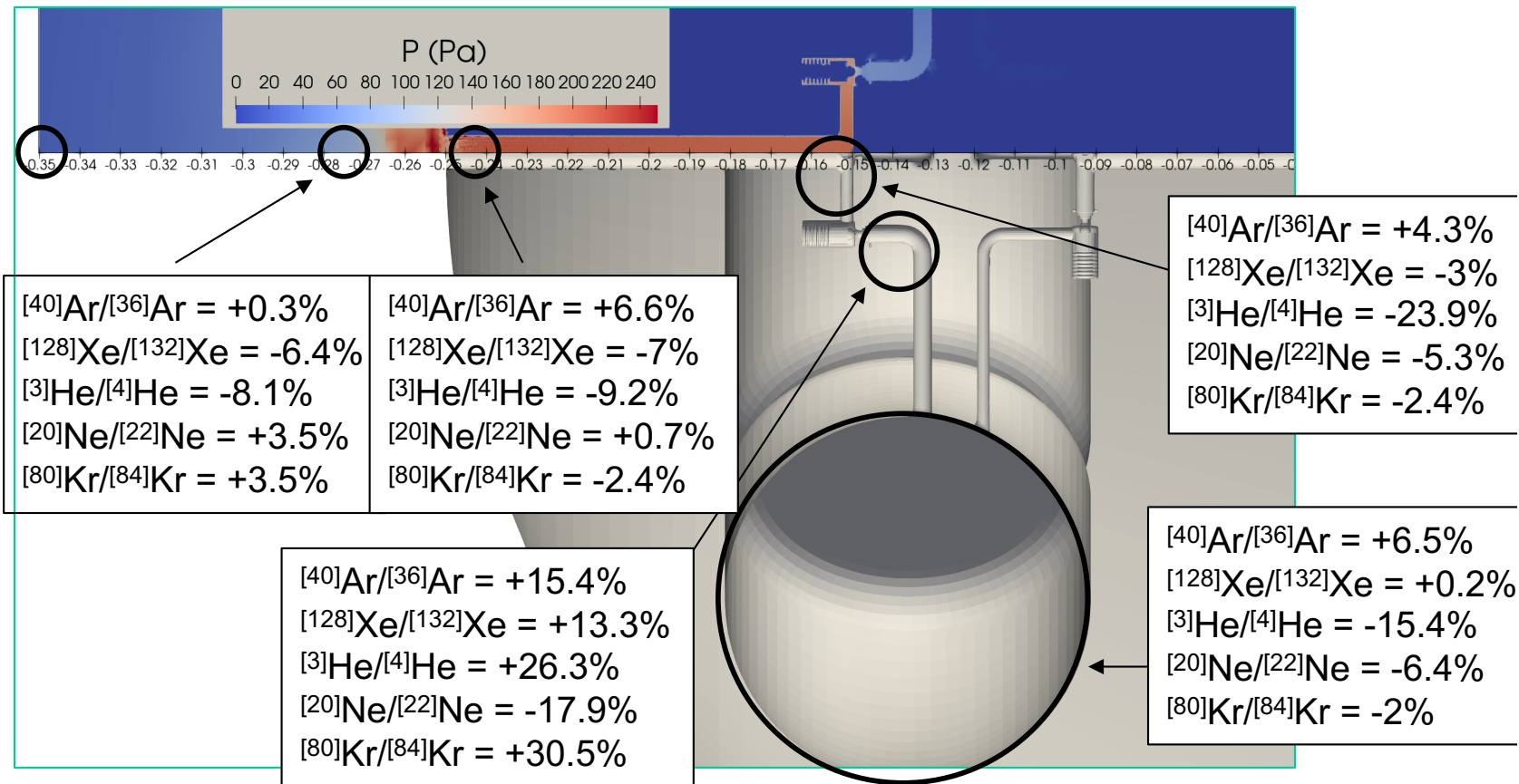


Comments:

- Variations in elemental ratios along stagnation line:
 - Elemental fractionation fully dictated by element molar weight
 - Non-negligible effect of valve on elemental ratios: some fluctuation post-valve
 - Return to pre-valve value in tank

Variation of isotopic ratios along stagnation line

Fractionation through the sampling system



Comments:

- Small variations in isotopic ratios along stagnation line:
 - Different isotopes only diffuse differently due to $\Delta(\text{mass})$; identical transport properties
 - Heavier species preferentially samples compared to lighter species
 - Very large variation of isotopic ratios post-valve, but returns to pre-valve value in tank

Ongoing and Future Work

Cupid's Arrow

- Sensitivity analysis matrix currently being completed.
- Verification of CO₂ transport and chemistry against experimental results:
 - Comparison with NASA EAST shock tube experimental measurements
 - Investigation of effects of chemical model
- Investigation of higher velocity Venusian entry (13.1 km/s): significant ionization?
- Ongoing discussions about adding a pinhole to slow down the tank pressure rise
- Backshell heating calculations
 - Currently assuming no TPS on the Cupid's Arrow backshell, and that high T solar arrays can withstand the entry environment
 - 2D axi-symmetric simulation to quantify backshell heating environment

Publications/Presentations

- **NASA Technology Reports (NTR) / Patent Applications**

- None

- **Conference Presentations and Proceedings**

1. Rabinovitch, J., Sotin, C., Borner, A., Gallis, M. A., et al. (2018) Feasibility of Hypervelocity Sampling of Noble Gases in the Upper Atmosphere of Venus. 16th VEXAG Meeting, 6-8 Nov 2018, Laurel, MD. LPI Contribution No. 2137, ID 8022.
2. Sotin C., Borner A. P., Gallis M. A., Rabinovitch J., Avicé G., Darrach M., Madzunkov S., et al. (2018) Sampling Venus' atmosphere to measure noble gases and their isotope ratios, AGU Fall Meeting, 10-14 Dec 2018, Washington, D. C.
3. Baker J., Sotin C., Rabinovitch J. (2019) Cupid's Arrow: Mission Concept and Overview, 13th IAA Low-Cost Planetary Missions Conference, 3-5 Jun 2019, Toulouse, France.
4. Rabinovitch J., Borner A., Gallis M. A., Sotin, C. (2019) Hypervelocity Noble Gas Sampling in the Upper Atmosphere of Venus. AIAA Aviation 2019 Forum, 17-21 Jun 2019, Dallas, TX.
5. Rabinovitch J., Borner A., Gallis M. A., Sotin C., Baker J. (2019) Cupid's Arrow: Hypervelocity Noble Gas Sampling in the Upper Atmosphere of Venus, International Planetary Probe Workshop 2019, 8-12 Jul 2019, Oxford, UK.
6. Sotin C., Borner A., Gallis M., Rabinovitch J., et al. (2019) Modelling the performance of Cupid's Arrow, a small satellite that would measure noble gases in Venus atmosphere, EPSC-DPS Joint Meeting, 15-20 Sept 2019, Geneva, Switzerland.
7. Borner A., Gallis M. A., Rabinovitch J., Sotin C. (2019) DSMC Simulations of Hypervelocity Sampling in Venus' Upper Atmosphere, DSMC 2019 Conference, 22-25 Sept 2019, Santa Fe, NM.
8. Rabinovitch, J., Borner, A., Gallis, M. A., Sotin, C., Baker, J., "Cupid's Arrow: Hypervelocity Sampling in the Upper Atmosphere of Venus," abstract and poster at the 17th Meeting of the Venus Exploration and Analysis Group (VEXAG), 6-8 November 2019, Boulder, Colorado.

- **Journal Publications**

- In work.

Thank you for your attention!

Questions?